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A Paper to be presented at the 120th Meeting of the American Institute of Electrical Engineers, New York, October 20th, 1892.

AN ELECTRICAL SURVEY IN THE BOROUGH OF MANHATTAN, NEW YORK CITY,

Showing Results of Stray Current Measurements Between Electric Railways, Underground Pipes, Etc., also Results of Tests on the Brooklyn Bridge.

BY A. A. KNUDSON.

The corrosive effect of straying currents upon underground metallic structures is now so well known and understood that obviously there is no need to dwell upon this fact as a reality, but rather it is the purpose of the author to show from actual tests, some of the locations and characteristics of the stray currents in New York city.

About eighteen months ago the question was raised by some of the municipal officers of this city as to the possibility of electric currents leaking or straying to underground pipes from the conductors of the "open conduit" electric railway on Lenox avenue, and adjoining streets at that time, as applications had been made to extend this system.

This matter was investigated at that time by the author, and some of the results becoming known to one of the officers of this Institute, he suggested that with some additional tests and the whole presented in a paper, it would prove of interest to the members and perhaps throw further light on this interesting subject.

I have since made a number of additional tests throughout the city, from Harlem river to the Battery, between various metallic structures such as "L" (Elevated railway) pillars, surface rail-

ways, water pipes, etc., and give the results here, trusting that they may prove acceptable, and possibly of some value.

Previous to making any tests on the Lenox avenue line, we had a well settled theory that in a double conductor system as this is, very little, if any of the current could be found diverted from the conductors to water or other pipes underground in its vicinity.

The tests were begun on Lenox avenue near the Metropolitan company's 146th street power-station, and continued south. From the first, unmistakable signs were encountered of railway current leakage from the rails of this road to both water and gas pipes, the sudden fluctuation of the voltmeter needle proving this beyond a doubt. It was noticed, however, that when a Lenox avenue car passed, there was no advance of the needle as should be expected, and when two cars passed, going in opposite directions, there was no advance of the needle at the moment; continuing down the street and testing at each fire hydrant and gas post the voltage tended to increase upon nearing 135th street. The readings during these tests were as follows, the rails being positive to the water and gas pipes.

Location	Water.	Gas.	Remarks
145th Street	1/6 volt	1/6 volt	
138th "	2/5 "	1/6 "	
136th "	2/5 "	2/5 "	
135th "	1/5 "	1/5 "	During this test no trolley car in sight on 135th street
135th "	3/5 "		Test repeated when the 135th street overhead trolley car crossed Lenox avenue tracks.
125th "	1/6 "		
116th "	1/5 "		
109th " and Columbus Ave	1/5 "		

It was apparent from these tests, that the most, if not all of this leakage, came from the Union railway company's line, operating the overhead trolley system, a branch of this road running through 135th street, and thereby crossing the rails of the Metropolitan company's tracks at Lenox avenue. This seemed the more certain from the fact that the maximum reading (3/5 volts) was obtained when a Union railway car was crossing the rails at Lenox avenue, or was quite near. Further proof, however, was necessary to determine if that company was responsible for all or only a portion of this current escape; advantage was therefore taken of the period when the Union railway

cars stopped running for the night at 1:30 A. M., to make some further tests.

At this time there were no fluctuations of the needle whatever, and consequently no sign of a trolley current escape from the rails to underground pipes. Tests were made over the same route as during the day, as well as at other places, but although the Lenox avenue line was running (they have an all night service) no evidence could be obtained of current straying from those conductors to either water or gas pipes. What we did find, however, worthy of mention, was another current, emanating from an entirely different source, passing from the water pipes to the rails, the pipes this time being *positive*, which, as will be perceived, was the reverse of the polarity found during the day. This current was as perfectly steady as if from a galvanic battery. The difference of potential, however, was low, in some places $\frac{1}{30}$th of a volt only was found, while in others the reading was $\frac{3}{10}$ths. In my efforts to identify this current I consulted the Manager of the power station, which supplied current to the Lenox avenue road, and he obligingly offered to shut down the plant for half an hour during that portion of the night when traffic is the lightest and give me a chance to re-test. This was done between the hours of 2:30 and 3 A. M., when both of these electric roads were then shut down so that no possible current could come from either one. The same steady current was found, however, as before, passing from the water pipes into the rails. The voltmeter proving insufficient as a means of completely identifying this current, telephone receivers were used, and with one at each ear there was no difficulty in recognizing the familiar sing of the incandescent dynamo. This test with the telephone was repeated several times by my assistant and myself so that there could be no possibility of error.

It appears from the tests made, that an open conduit system, or one in which an insulated metallic return is used, effectually confines the current to the conductors provided for it. For this reason it is preferable to the ordinary ground return, especially in large cities, where the space below the streets is so largely occupied with various lines of iron pipes, more or less subject to electrolytic action.

The distances the overhead trolley current would sometimes reach, were shown by a rise in voltage when a Union railway car

crossed the tracks of the Lenox avenue road at 135th street. This was found as far down as 116th street, where the latter road branches east and west; in fact, there was no portion of this road where these trolley current fluctuations could not be obtained when cars were passing through 135th street.

Desiring to learn the difference of potential between the elevated railway piliars, and water pipes, with the Union railway, if any, in this part of the city, tests were begun at 157th street (Harlem River) on the Eighth avenue line and continued down as far as 109th street, which is the western terminus of the Metropolitan company's open conduit system. Rather than make this paper monotonous with long tables of tests, some plans have been prepared of different locations in the city,

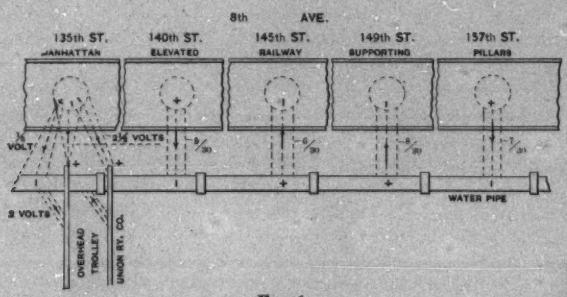


Fig. 1.

showing where these tests were made, and giving the difference of potential at the points indicated. It may be well to state here that the voltmeter used was a Weston two scale; the lower scale reading to 5 volts with 30th divisions; this scale was used in most of the tests, and accounts for the record being given in a number of cases in thirtieths of a volt. The upper scale read to 150 volts in 1 volt divisions.

The following is a general description of the method of procedure touching in detail at such points as may be of interest.

The starting point as already stated was at 157th street; from this point down to 135th street the tests are given in a table, as well as in plan, Fig. 1. The table giving both day and night tests for comparison, while the plan gives the day tests only.

The Union railway (overhead trolley) heretofore spoken of as

passing through 135th street, terminates at Eighth avenue; in fact, the ends of the two trolley wires of that road are supported by being attached to the "L" structure which as is well known passes through that avenue.

Location.	Day test 9 to 10 A. M.	Night test 1:30 to 2:30 A. M.
157th Street	"L" + to Hydrant 7/30 Volt.	7/30 Volt "L" + to Hydrant
149th "	"L" − " " 8/30 "	3/30 " "L" + " "
145th "	"L" − " " 6/30 "	1/30 " "L" + " "
140th "	"L" + " " 5/30 "	2/30 " "L" + " "
135th "	Rails U. E. Ry. + to "L" 2¼ volts	2/30 " Rails + "L" Ry.
135th "	" U. E. Ry. + " Hydt. 2 "	
135th "	"L" + to Hydrant ½ volt	1/30 " "L" + " Hydrant
		Night readings steady throughout.

Referring to the table, it will be noticed that the reading at 157th street shows that the night test was the same as during the day. It was afterwards discovered that the last car of the Union railway had not then left the track, which accounts for this reading being higher than the other, as well as a trolley variation being shown. All of the other night tests, however, showed the same indications of an incandescent current as were found on Lenox avenue, as well as at several other places. One feature worthy of notice in the day test, shown in the plan, as well as the table, is the change of polarity found at different points on this section of the road.

The current passes into the water pipes and "L" structure from the rails of the trolley road at 135th street (they being positive) from 2 to 2½ volts maximum, then along the pipes for five blocks to 140th street, then reverses and passes along the "L" structure for another five blocks to 145th street, where it again reverses and takes the water pipes to another reversal at 157th street.

The cause of this erratic jumping of the railway current up some pillars and down others may be explained in two or three ways, two of which I will mention:

1st. Proximity of water pipes to the "L" structure, at some points being closer than at others, offering a more favorable path for this portion of the current.

2d. The current passing into the water pipes at 135th street as well as the "L" structure at the same polarity, and possibly at a higher voltage at times to water may cause this change in polarity at different points along the line.

A few days ago tests were made over this same section of road with almost identically the same readings in each case as prevailed over a year ago. It was noticed, however, that the terminal rails of the Union railway company at 135th street and 8th avenue had recently been replaced by new ones which appears to be a good illustration of "cause and effect."

Similar conditions also prevail on the section of road below 135th street down to 109th street. At this point the "open conduit" road has its western terminus. Day tests have shown a maximum reading of $\frac{1}{8}$ of a volt, the rails being positive to "L" pillar, and to water, the night test when Union railway was not running, $\frac{3}{10}$ steady, showing plainly that the current was from that road.

Attention is now directed to the east side of this part of

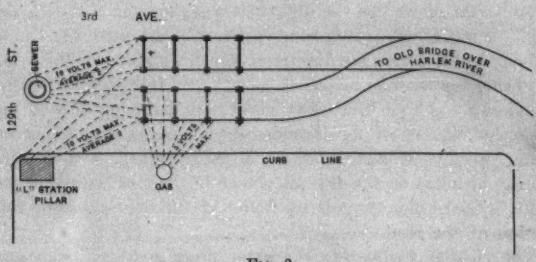


FIG. 2.

the city where another branch of the Union railway is located. Tests made here show even more pronounced results than at the branch running through 135th street to the west side. It may be stated that the power-station of this road is located on the Bronx river in Westchester county.

Something more than a year ago when these tests were made, this branch had a terminus at Third avenue and 129th street, immediately in front of the "L" station, the cars then passing over the Harlem river at the old wooden bridge, which is now being removed. The cars now pass over the public bridge recently opened, to the new terminal at Lexington avenue. Fig. 2 shows the location of the terminal when these tests were made, as well as the difference of potential.

It will be noticed that the maximum reading here was 10 volts,

rails positive to "L" pillar, sewer, and gas. A test was also made on the Harlem bridge, which showed the same reading,

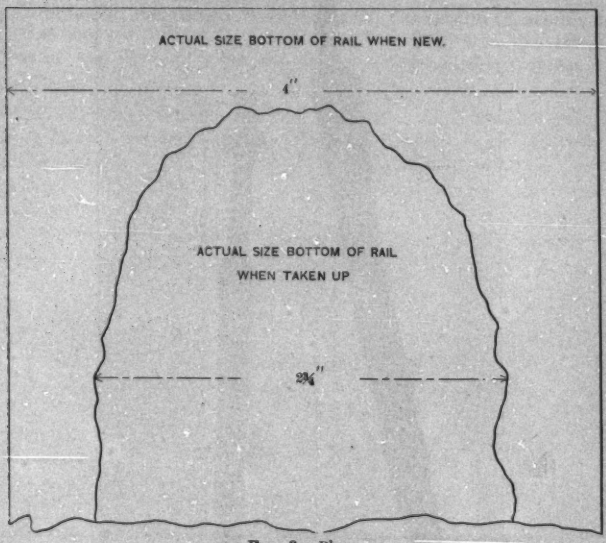


FIG. 3. Plan.

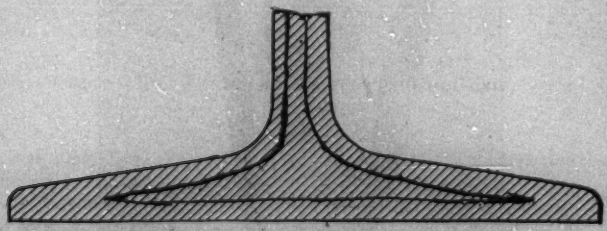


FIG. 3. Section

except it was made to gas only, no other pipes being at hand. A few days ago this locality was visited with a view of obtaining

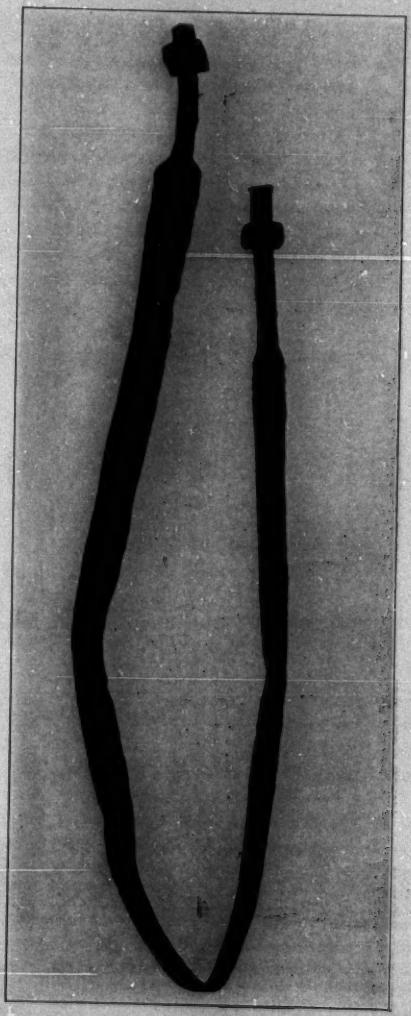


FIG. 4.

any further items which might be of interest for this paper, and workmen were found engaged in removing the rails of this very terminal.

Information was therefore obtained as to the results of electrolytic action on these rails (they having been positive). An impression was taken on paper of the exact size and shape of the

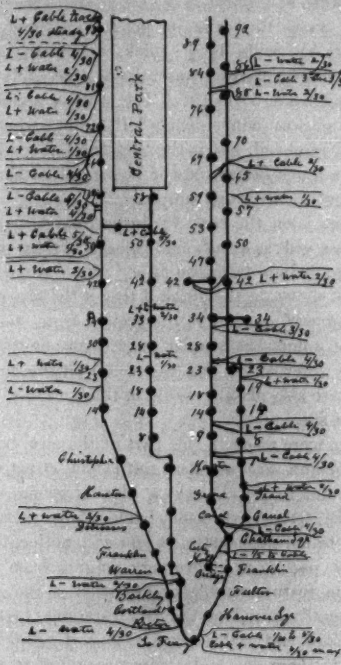


FIG. 5.

end of one of the four rails which composed that terminal switch, the ends of the other rails all being in just about the same condition. Fig. 3 shows a comparison of the size and shape of the rail when new and its present condition; the position of the outlines as to each other being about as shown. From the condition of these rails now, it is quite plain that a large amount of metal

has been removed from them by electrolysis. The original size of the rails was furnished by the company supplying the rails, they being 70 lbs. to the yard; furthermore, the bottom sides of all these rails were cut by the current down to knife edges for several feet back from the ends. These edges were irregular in shape and somewhat jagged in appearance.

Another feature of interest is the condition of the cross-bars or tie-rods which keep the rails in position. These bars, which were originally $1\frac{1}{2}''$ wide by $\frac{3}{8}''$ thick, were nearly all so eaten away that the middle portion was missing, the ends protruding from the rails at from 6″ to 12″. Fig. 4 gives a view of one of these bars which was conveniently left behind when the other materials were removed. It is the only one I saw which was intact, and is in a much better state of preservation than the others, consequently not an average sample.

This specimen is on the table for inspection by those who care to examine it, as well as some small pieces, broken off by hand which were protruding from the rails. Your attention is called to a feature not shown in the cut and that is the sharp knife-edge of the side that was deepest in the ground from where the current passed out, somewhat similar in appearance to the sides of the rails above referred to; the ridges and pitting characteristics of electrolysis are also plainly visible in this, and in a lesser degree in the smaller specimens.

Further tests were made in this part of the city, but being not specially important, are omitted until 93d street is reached, from which point to the Battery a plan is given, showing the locations where tests have been made, their voltage and polarity. These tests refer mostly, as you will notice, to the incandescent current, passing at low voltage, ranging from 1/30 to 1/5 of a volt. One feature worthy of attention is the lowest reading being generally found at the "L" stations, between pillars under the stations and water pipes. This is accounted for by the fact that as there are water pipes supplied to most if not all the "L" stations they would make a fairly good electrical connection with the structure itself, and, therefore, not much difference of potential could be expected. This point also suggests a method for remedying this condition of affairs. Coming down the west side of the city, I was surprised to encounter a full fledged trolley current in the extreme lower part of the city. The first intimation was found at Rector and Greenwich streets,

it became more pronounced in the vicinity of South Ferry where in testing between the rails of the Metropolitan cable road and an "L" pillar, a variation of from 1/30 to 8/30 volt was found, the rails positive, and the same reading between the rails and water pipes.

Just why there should be indications of a trolley current in this part of Manhattan Island was difficult to understand, but after making further tests coming up on the east side, this current was found to come from the Brooklyn bridge. Having pointed out how an overhead trolley, using the water pipes and incidentally the rails as a return, such as is operated on 135th street, can spread its influence, so to speak, for a distance of over 20 blocks in either direction north and south, through various pipes, railway structures, etc., the existence of this current from the bridge permeating underground metals through a large portion of the lower part of the city, is accounted for.

The tests were continued at the New York entrance of the bridge, and at the pillars which stand in the street just west of the Third avenue cable railway, I found the readings as follows: At one pillar a maximum of three volts, average 1½ volts, pillar positive to Third avenue cable rails. At another practically the same reading. Further up Park Row at the corner of Chambers street, pillar positive to cable rails, 1 volt maximum; water positive to cable rails ½ volt; pillar positive to water 1/3d of a volt.

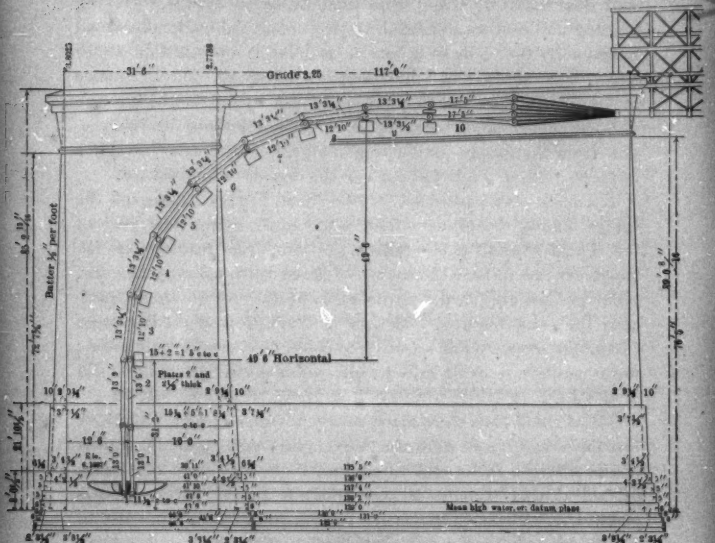
All of these tests were made nearly a year and a half ago. A few days ago, tests were made over this same ground, and at places where a difference of potential of three volts maximum existed at that time, it is now found to be 3 1/5 volts, pillars positive as before to rails of Third avenue cable and also to water pipes, showing in all probability that this current has been during all this time actively and unceasingly passing down the pillars which support the "L" station at this place, as well as the bridge crossing the street, and out from their foundations to other metals as stated, with now a fifth of a volt more for good measure.

In the light of present knowledge on this subject the very serious question presents itself to any practical mind here present, in what condition would we expect to find the anchor bolts and iron foundations of these pillars, if excavations were made at their base?

In Mr. Farnham's excellent paper read before this INSTITUTE four years ago, he showed that but a small fraction of a volt was necessary to establish electrolytic action between metals.

What then can be expected from an incessant action of from 1¼ to 3 1/5 volts jumping out of these foundations during the past year and a half or perhaps two years.

Further tests at the New York entrance of the bridge at pillars nearest the four loop tracks, show that they are nega-



ELEVATION

FIG. 6.

tive to rails of these tracks with maximum voltage of 3¼ an estimated average of 2¼. These tests were made on three different days at different times of the day, the highest maximum reading as above being taken at 4.45 P. M.

The other tests, one made during the so-called rush hour between 5.30 and 6 P. M., where a maximum reading of 2 1/5 volts noted at track 1, did not vary much from the tests made in the afternoon of another day at from 2 to 2:30 P. M. at

track 4, where the voltage was found to be $2\frac{1}{3}$ maximum. Previous to any use of electricity for operating cars on the bridge it had been known that currents were escaping to that structure from trolley lines in Brooklyn, and passing over would find their way through the city by underground pipes, etc., and thence crossing the river arrive back to the power-station in Kent avenue.

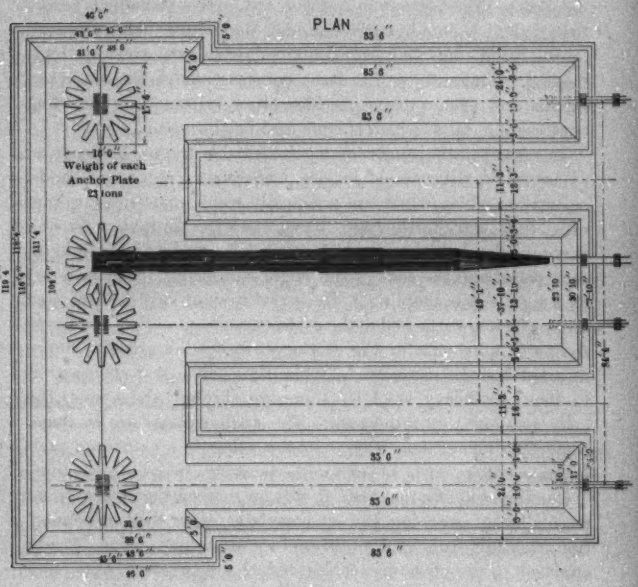


FIG. 7.

The polarity of both of these railway systems now operated on the bridge, indicates that these currents escape from their lines, but it is also quite likely that currents are even now coming over the bridge as they were a year ago. Only an extended investigation would determine these points, even if it were desirable that they should be known.

Let us now take up the investigation made on the bridge to deter-

mine if possible the movements of straying trolley currents and their possible effect on the cable terminals. In view of the importance of this matter I regret not being able to make it more thorough than here stated, as it would involve not only a fortnight's work at least, but the shutting down of the bridge plant for a time, which could hardly be expected under the circumstances. Such facts are represented however as it was practicable to obtain. Recognizing the necessity of having every detail as to the construction, location, etc., of these terminals before being able to intelligently consider the matter, plans prepared by the bridge engineers were obtained which are given in Figs. 6 and 7. These show the exact construction of the cable terminals and anchor plates, besides other information regarding construction, all of which is from an official source.

In regard to the construction of the cable terminals; as most of us know, the main cables are made up of eighteen strands, or smaller cables, which are practically continuous, the wire running back and forth from New York to Brooklyn, passing through the holes at the ends of heavy steel bars or links at each place, and the ends of the single wire being finally fastened by a rigid screw coupling. These two rows of steel bars of nine each, which are attached to the cable strands, one row placed over the other, as shown in Fig. 6, pass down with a graceful curve into solid stone masonry to the anchor-plates, and are secured to them by heavy steel bolts passing through the eyes at the ends, as shown in the figure. The anchor-plates are in shape somewhat longer one way than the other (see plan), and each being a single piece of cast-iron, weighing twenty-three tons.

Coming now to the tests, it will be noticed that there is no possibility of reaching the anchor-plates other than by connection through the cables themselves, and they being firmly attached to the structure, cables and all are practically one conductor; and a connection on the structure would mean connection with the cables, and consequently with the anchor-plates.

This point therefore being settled, the next thing was to obtain a suitable ground, and on the suggestion of Mr. C. B. Martin, the electrician of the bridge, one of the railway cables was used during that portion of the day when it was not in operation for hauling a bridge train. This was a convenient as well as a good ground, the cable surface being polished bright through friction in passing over the pulleys, it

was possible to obtain a good contact, and as it passed over the large drums in the engine-room which were on foundations connecting with engines, water-pipes, etc., it was probably the best ground independent of the structure obtainable. The connection to the structure was made by the use of a two-inch screw-clamp, the wire to the voltmeter being attached to it by the simple means of a screw and washer. Two of these clamps were generally used in nearly all of the previous tests, as they were found very convenient for attaching and detaching quickly to and from hydrants, pillars, etc. The first test under these conditions was made just over the Brooklyn anchorage, where the structure was found to be positive to the ground, with a difference of potential of $2\frac{1}{4}$ volts maximum, estimated average $1\frac{1}{4}$ volts.

At the Brooklyn tower another ground connection was made to a water-pipe, which ran down the side of the tower, and is intended for use in case of fire on the bridge. At this point the reading was $3\frac{3}{4}$ volts maximum, average $2\frac{3}{4}$, bridge structure was as before positive. At center of span, structure positive at first, with $2\frac{1}{4}$ volts maximum, but during the readings there were two reversals, one of them only remaining long enough to obtain a reading, which was $1\frac{1}{4}$ volts maximum, structure negative. At the New York tower: structure positive to cable ground, with trolley variations ranging from $\frac{3}{4}$ths to 3 volts, average 2 volts. At New York anchorage: maximum $2\frac{3}{4}$ volts, average 2 volts, structure positive, to ground.

Other tests were made to determine the polarity of the rails of the bridge trains, and they were found positive to the structure, the same as the rails of the trolley road heretofore tested. Let us now consider the question of the electrolytical conditions of the cable anchorages, as this point appears to be of high importance in this matter, if not the key to the whole situation in determining whether or not electrolytic action is going on. First: These anchorages are composed of solid stone masonry and are put together with the highest quality of cement; there is no brickwork or mortar in their construction.

2d. The 23 tons of iron composing the plates are set about 80 feet below the top of the anchorage. The distance from the bottom of the plates to mean high water is 3 feet 8 inches at the New York end, 5 feet at the Brooklyn end; there is no earthy matter, salts or alkalies, such as is found prevalent in the streets which go to make up an electrolyte, so I am informed, in any part of this structure.

I was at first apprehensive that on account of the comparatively short distance between mean high water and the plates at both anchorages there might be opportunity for salt water to reach the plates through seepage or capillary attraction and thereby produce such an electrolyte as to cause corrosion, but have been informed that it is not possible for salt water to reach these terminal plates on account of the distance from the river, the anchorages being over 900 feet from the towers which stand at each side of the river. Even allowing 100 feet for the salt water to work back, there is still ample margin as to distance before salt water can reach these plates; besides this, one of the bridge engineers showed me a plan of the construction of the foundation under each anchorage, which consists of heavy timbers 10″ x 10″ and some 12″ x 12″ arranged in 4 to 7 layers, placed a short distance apart, and the intervening spaces filled in with concrete cement.

In view of the tests therefore that have been made showing the structure and cables to be positive at both ends, it is quite possible that a portion of the currents straying from the trolley lines, and possibly from the bridge service, find their way out of the anchor plates through the dampness of the stone-work of these anchorages. The construction of these anchorages however is such, as I have endeavored to set forth, that it seems reasonable from the general construction of these piers that the mass of stone and concrete surrounding these plates will not constitute an electrolyte such as would favor electrolysis, and thereby cause corrosive action on them.

One of the bridge officials informed me that a certain authority had reported that electrolysis would not attack cast-iron, consequently their cast-iron anchor-plates were exempt from such danger. In the light of recent experience in other cities, that theory is now untenable; for instance, I will quote a few extracts from a pamphlet, giving the reports of four experts, besides that of the Secretary of the Water Board of the City of Dayton, Ohio, embodying an estimate of cost for repairing the damage.

Mr. E. E. Brownell, C. E., states: "To my surprise I have found in this city a six-inch water main that was corroded to the depth of one-quarter of an inch where the voltage did not average over 1.5 to 2 volts positive to the rails, therefore it is impossible to establish a certain voltage that will cover all cases for low readings."

The following extracts are quoted from the report of Mr. J. H. Shaffer, metallurgist:

He says: "In accordence with instructions from the Board, I have made a careful inspection of the cast-iron water mains at fifteen different locations in the city," and then gives the results of excavations, etc., two of which I will quote.

1st. "This excavation was made at the corner of Washington and Mound streets. It exposed a six-inch main and a ten-inch tee; the pipe was laid in 1874, and the tee in 1888, both were subjected to electrolytic action for about ten years. Both pipe and tee showed great evidence of electrolytic corrosion, the pipe being damaged to an alarming degree, with holes pitted from one-eighth to five-sixteenths of an inch in depth, and covering a large portion of the same.....The lead caulking was found to be in bad condition, and showed perceptible evidence of leaking. The pipes at this point were nine volts positive to the rails.

"2d. This excavation was made on Germantown street, near Krug. It uncovered a six-inch pipe. This pipe was electrolytically corroded in about the same proportion, with other conditions identical. A lead service pipe was also exposed at this point, and was found to be entirely destroyed."

A quotation from the report of the secretary on an approximate estimate of the cost of replacing water-pipes damaged by electrolysis caused by electric railway currents may also be interesting.

He says: "In calculating the cost of replacing the pipes in the whole affected territory, it is estimated at $77,208.80.

"There is 17,513 feet of pipe that shows a voltage of from two to nine volts positive, and from pieces of pipe removed where electrically charged to this extent, it is found that they have deteriorated fifty per cent. in four years.

"Where they were required, when laid, to withstand a hydrostatic pressure of over 300 pounds per square inch, when tested by J. H. Shaffer, iron expert, after being subjected to 4.5 volts for four years, leaked at 150 pounds pressure."

He also states the following: "At 4.5 volts it has been shown that a six inch pipe can certainly become useless in 5 years."

I have quoted thus freely from this pamphlet for two reasons, one to show that it is a mistake to suppose that cast-iron is not subject to corrosion by electrolysis produced by railway currents, and also to show the penalty to which a city is subjected through permitting such conditions to exist so long that they cause such heavy damages to its property. In the light, therefore, of what has been shown to be the state of affairs in the upper part of this city due to escaping railway currents, as well as the experience

at Dayton, O., it appears to be the duty of engineers to exercise every possible precaution against the effects of this invisible element of destruction, which if left to itself will certainly shorten the life of valuable city property.

In the cases found to exist up town it is true that the rails of the road referred to are apparently the principal metals damaged, for the reason that they happen to be positive to the water pipes, but as the escaping current goes into the pipes at one place it must come out at others, and at these places damage may be looked for.

The damages already done and threatened to public works in England by electrolysis has led to the establishment of regulations to prevent such action in the future, and similar legislation may be expected in this country should these conditions be allowed to continue. One of the provisions in the regulations prescribed by the British Board of Trade may be of interest just here. It is to the effect that if the pipe is negative to the rails the potential difference shall not exceed 4.5 volts, and if the pipe is positive to the rails the potential difference shall not exceed 1.5 volts. This appears to be very liberal for the railways, in view of the experience in cities on this side of the water; it is probable however they will be made more stringent as future experience in this direction dictates.

I have purposely avoided elaborating any particular scheme for preventing damage by stray railway currents in this paper, for the reason that methods are perfectly well known to railway companies for confining currents to their proper conductors, such as efficient bonding, and providing a return that will leave no inducement for the current to seek underground pipes, in preference to a legitimate conductor. It is simply a question of additional expense. Referring to the incandescent light current which was found prevailing everywhere in this part of the city from the Harlem river to the Battery, passing between all kinds of underground metals, and some on the surface, I do not consider these currents as particularly dangerous at the moment on account of their low voltage, but as before stated, it having been established that a fraction of a volt difference of potential will cause electrolytic action, it then comes down simply to a question of time, when those straying incandescent currents will have to be seriously considered.

In conclusion, I wish to say that these remarks regard-

ing possible damage to public structures through the action of electrolysis, have been made with no desire on my part to appear as an alarmist, but to present simple facts as found in these investigations. I believe that too little attention has heretofore been paid to this matter by any of us; perhaps for the reason that electrolytic action being invisible, as well as noiseless, it has thus escaped attention, and its baneful effects not fully appreciated. It is my opinion, however, that ordinary caution would suggest, that periodical tests should be made in every city by competent parties where a trolley road using a ground return is in operation, and the reports placed before those having authority to deal with the matter. In this way threatened damage by electrolysis to water and other pipes, as well as bridges, might be arrested and finally controlled.

[See page 327, May Issue.]

[COMMUNICATED AFTER ADJOURNMENT BY CHARLES P. STEINMETZ.]

The striking distance is constant from 40 to 125 cycles, and probably for some range outside thereof. At zero cycles, that is, continuous electrostatic stress, a deviation may occur, due to a difference of the mechanical motion set up in the medium.

Of very high frequency as 100,000 cycles or so, nothing can be said, since no means exist to measure voltages at such frequencies. Calculation from the constants of the circuit is not possible, since these constants may be entirely changed at very high frequency. The ratio of transmission gives entirely wrong results, due to capacity and self-induction, and no instruments that I know of can measure the maximum values of very high frequency oscillations.

The only means of producing very high frequency is the condenser discharge, and this does not give constant potential, but is a limited power method in which the potential depends upon the conditions of the circuit.

There appears to me no reason, however, why the striking distance for a given voltage, with sufficient power behind to maintain this voltage, should be different at very high frequency, and in the absence of any satisfactory means of measuring voltages at such very high frequency, I should rather be inclined to estimate voltages from the striking distance, even at such frequencies, and do not believe that such estimates would be very far wrong.

Regarding the reason for choosing the arrangement described, of four separate transformers, it was done for safety, and considered desirable when these transformers were built, four years ago. Since that time single transformers for 100,000 volts have become a standard article of manufacture, for testing purposes, and are at this writing no great curiosity. But still, a great difference exists in the electrostatic stress at 100,000 and 160,000 volts.

Schenectady, N. Y., Sept. 13, 1898.

A paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 30th, 1898. President Kennelly in the Chair.

HIGH-VOLTAGE POWER TRANSMISSION.

BY CHAS. F. SCOTT.

Several years ago an investigation of the conditions and requirements incident to the use of high voltages was undertaken by the Engineering Department of the Westinghouse Electric and Manufacturing Company. In this experimental investigation the size of the apparatus and the conditions of the tests were as far as practicable such as would prevail in actual work.

The transformer, the *sine qua non* of high-voltage working, received first consideration. A design suitable for large sizes was worked out and tested; then high-voltage windings were made. Attention was next directed to the line insulator.

New phenomena were liable to be presented at higher voltages and it was necessary to determine what they were, also how to meet the requirements which they impose. New forms and sizes of insulators were designed, made and tested to determine the losses which would occur and the limit at which they would break down.

The luminosity and the hissing sound emitted by the connecting wires of high voltage, suggested a loss which might be an appreciable addition to that over the surface of the insulators. It was found that a very considerable loss of energy took place between the wires—a loss which at high voltages was much in excess of that across the surface of the insulators.

Mr. L. L. Nunn visited Pittsburg at this time and became much interested in this work. He was a pioneer in power transmission, having put in the first large alternating current transmission plant in this country, namely, that at Telluride, Colorado,

which was designed by the writer and described by him[1] at the General Meeting of this INSTITUTE in 1892. It was proposed that this work be taken up conjointly by the Westinghouse company and Mr. Nunn, and prosecuted on a much enlarged scale, by operating the original motor over a high-voltage line. In a report to the Vice President and General Manager of the electric company, dated April 2nd, 1895, the writer said, "The transformers would be arranged to give a line pressure of 10,000, which is to be increased by suitable steps to possibly 50,000 volts.....I regard this as an excellent opportunity to make a thorough and extremely important and valuable test of high-tension working under difficult practical conditions, which our company should take up and carry out as fully as possible." Raising and lowering transformers were made and sent to Telluride, and power for the 100 H. P. synchronous motor was transmitted at voltages far exceeding any which had been previously used anywhere. Exceptional facilities were afforded for observing the practical operation of high-tension working under severe climatic conditions, and for making measurements. The results of the work were so assuring that the Telluride Power Transmission Company has lately installed a plant which is in commercial operation at 40,000 volts and is now making an increase in the plant. This work has been continued on experimental circuits at East Pittsburg, and some measurements have been made at Niagara.

The work which has just been briefly described was an investigation into an unknown field. It has been progressively and systematically carried out and it has determined results which were unforeseen, and which are of both theoretical interest and practical importance.

This present paper describes the more interesting and important parts of this work and gives the methods by which measurements have been made and the results which have been reached. A number of points of interest and importance are given with regard to long-distance transmission plants now in operation.

HIGH-TENSION TRANSFORMERS.

In 1891 the Westinghouse company furnished transformers for the 10,000-volt transmission to San Bernardino and Pomona. Twenty transformers were used in a set, each giving a pressure

1. TRANSACTIONS, vol. ix, p. 425.

of 500 volts and the twenty in series 10,000 volts. This arrangement made the insulation within the individual coils a matter of comparative ease. The insulation between the coils of the high-tension circuit and other parts of the transformer was secured by allowing a space, which was filled with oil.

The first arrangement of transformers for giving from 30,000 to 50,000 volts was made by using a number of transformers, each giving 10,000 or 15,000 volts. The low-tension circuits of the several transformers received current from an insulating transformer in which there were a number of separate coils, each one supplying a separate raising transformer. An arrangement of this kind was used for obtaining the high voltages in the exhibit of the Westinghouse company at the World's Fair. A large transformer was designed in January 1894. The output of 200 K. W., was many times greater than that of any transformers which had been made by the Westinghouse company. The transformer was oil-insulated and was cooled by water flowing through a pipe immersed in the oil. This transformer was pronounced a success, and the type was adopted and has been followed ever since as a standard, except that the water-cooling is employed only on the largest sizes.

The transformer was then rewound for 40,000 volts, and a somewhat reduced output. It was operated at this voltage for a short time, when it was found that through an oversight, the insulation between layers was insufficient. In October the high-tension coils were rewound for 60,000 volts and the transformer is still in use after many months of varied service and a considerable period of inactivity.

The making of a single large transformer for a very high voltage naturally involved new difficulties. Above 10,000 or 20,000 volts there was an unexplored and uncertain field in the matter of insulation. Materials which were commonly used at ordinary voltages might have very different characteristics under the new conditions. Tests were ma e on materials before the first high-voltage transformers were made, and it has been continued. The large high-tension transformer as made to-day was not designed in a week or a month, but it has been an evolution based upon experimental tests and experience in continued operation.

High-Tension Insulators.

After a high-voltage transformer was constructed, the insulator naturally presented itself as a fundamental factor in transmission. The requisites of an insulator for high-voltage work are, that it shall have a dielectric strength sufficient to prevent the current passing directly through the material, that its dimensions shall be large enough to prevent the passage of current over the outside of the insulator to its support, and that the resistance, both of the material and its surface, shall be sufficiently high to prevent undue loss of energy. In addition to these fundamental electrical requirements are those of a mechanical nature involving strength and convenience. These properties must of course be permanent, and not liable to deterioration while in service.

Up to this time very little attention had been given to the manufacture and design of high-tension insulators. There were available for our laboratory tests the glass insulators which we had designed for the 10,000-volt transmission line at San Bernardino and Pomona, California. (See paper of Mr. G. H. Winslow[2] before the General Meeting of the Institute in 1895).

A much larger glass insulator was made having the so-called "helmet" form, which was probably the beginning of a type which is now quite common. The large glass insulator presented mechanical difficulties in manufacture, and recourse was had to porcelain. An insulator was designed to be under-hung, the top of the insulator being supported in an inverted cup which was to be bolted to the under side of the cross-arm. From the bottom of the insulator a pin extended which was anchored in a hole in the insulator and held the wire several inches below the porcelain. The object was to place the wire below the cross-arm so that the snow which might pile up on the cross-arm would not come near the insulator. The wire, moreover, instead of being supported upon the top of the insulator, where it is in connection with an extended wet surface, would be supported from the part of the insulator which is most protected and the dryest.

An interesting evolution then began to take place in the manufacture of porcelain. There were eight or ten steps in this history, in which insulators which were presumed by the manufacturer to be satisfactory were broken down on high-voltage test. Porcelain which presented a beautiful smooth glazed surface was

2. Transactions vol. xii p. 405.

often found to contain internal cracks or cavities which were soon traversed by the current. In other cases bits of pebbles or other impurities were found. In still other cases the porcelain was not homogeneous and was not compact, or the material was porous and absorbed a drop of ink almost as readily as a lump of sugar would do. The effect of this work is seen in the improved quality of material now made by certain porcelain manufacturers who benefited by this experience. It may also be remarked that some of the unpleasant experiences with porcelain insulators might have been prevented if similar preliminary tests had been made instead of employing the more expensive and inconvenient method of testing them in commercial service.

The under-hung form of porcelain insulator, however, did not prove successful nor satisfactory. The insulator was heavy and cumbersome, and no satisfactory method was devised for holding the wire. A wooden pin lacks strength, and a metal pin reduces insulation. Moreover, smaller insulators of the ordinary form were found suitable for higher pressures than was anticipated.

Some measurements were made of the losses on the Pomona insulators. Twenty-four insulators were mounted on wooden pins. A wire was run along the tops of the insulators and a second wire connected the pins. The increase produced in the reading of a wattmeter in the primary of the raising transformer when the wires were connected to the high-voltage terminals, was taken as the loss on the insulators. The loss at 23,000 volts was about two watts per insulator. This voltage between pin and wire corresponds to 50,000 volts between transmission wires.

Losses Between Wires.

The loss over the surface of insulators was quite small, in fact almost insignificant compared with the amount of power which would ordinarily be transmitted. The various displays of energy about high-tension wires, led us to investigate and determine whether this loss was one of importance. In order to measure the loss between wires, eliminating what occurs on the insulators, it was desirable to have a considerable length of wire, to support it without insulators, and preferably to arrange the wires in such a form as to give a considerable loss. Nine wires each 60 feet long were stretched 4″ apart in a horizontal plane and were held in place by strings several feet in length at each end. The wires

were No. 19 B and S gauge, 0.036″ in diameter. They could be connected in various ways, and any pair or pairs of wires could be omitted as desired.

The power supplied to the raising transformer was measured by a wattmeter placed in the primary low-tension circuit. When the load was placed on the transformer, the wattmeter reading increased, and the amount of increase was taken as the power delivered to the load. This method involves certain errors which will be pointed out further on, but on the whole it gives an approximate and fairly correct indication of the power, and is sufficient to show clearly the general form of the loss curves and a number of interesting characteristics.

The first measurements of this loss are recorded Feb. 26, 1895. The 1st, 3rd, 5th, 7th and 9th wires were connected in multiple to one terminal, and the other wires were connected to the second terminal of the raising transformer; successively increasing voltages were applied.

The wires began to give a hissing or crackling sound and in the dark began to appear luminous at a little below 20,000 volts. As the voltage was increased the sound became more and more intense, the wires vibrated and became more and more luminous, until at the higher voltages they were surrounded by a coating of soft blue light many times the diameter of the wire. Often there were bright points along the wire, probably corresponding to bits of dust or rough places resembling points on the wire. The large room soon became strongly charged with ozone.

Results of measurements on all wires, alternate wires being connected together to one terminal, and the intermediate wires to the other terminal of the raising transformer, are given in the accompanying Fig. 1. Three curves are given for a frequency of 60 periods per second, or 7200 alternations per minute. Two of these curves give the wattmeter readings for the different voltages, one for the transformer alone, and the other for the transformer and high-tension wires; the third curve gives the difference between the two, and therefore represents approximately the loss on the high-tension wires. Corresponding curves are given of tests made at a frequency of 133. The loss in the transformer is less at the higher frequency but the loss on the high-tension wires is almost the same for both frequencies. These losses are very small below 18,000 volts, but increase

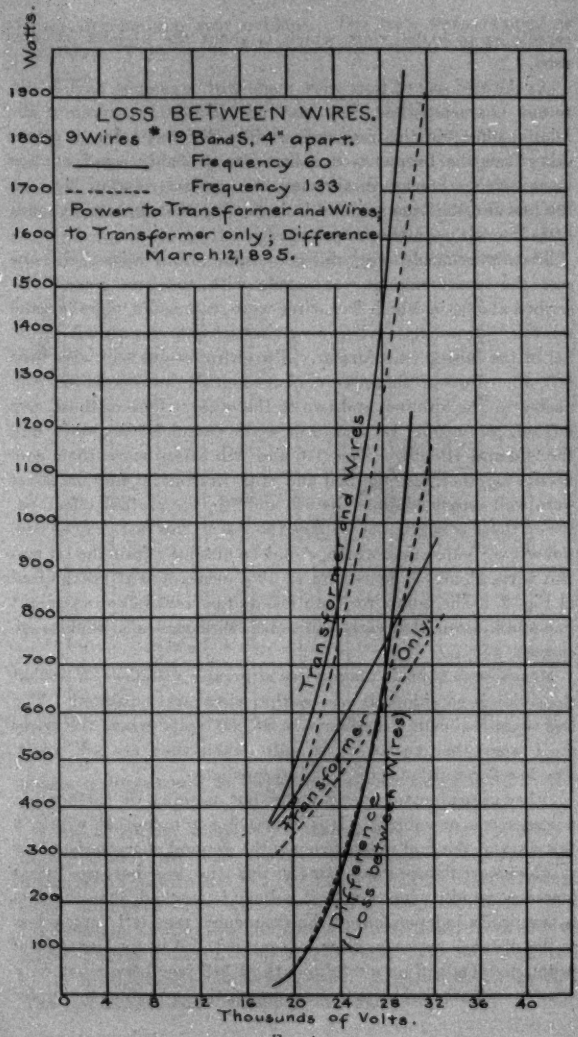

Watts.
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
LOSS BETWEEN WIRES.
9 Wires * 19 Band S. 4" apart.
Frequency 60
Frequency 133
Power to Transformer and Wires, to Transformer only; Difference
March 12, 1895.
Transformer and Wires
Transformer only
Difference (Loss between Wires)
0 4 8 12 16 20 24 28 32 36 40
Thousands of Volts.

FIG. 1.

rapidly up to 30,000 volts, which is about the highest pressure used.

As the two sets of tests were made with dynamos having different characteristics, they may not accurately represent the relative effects of the frequencies. The difference due to causes other than the frequency are, however, probably small, so that these tests are correct in showing the general relation between the loss and the pressure, and in indicating that the loss depends little if at all upon the frequency.

Tests were made with different numbers of wires. In one case the measurements were made with the arrangement described above, in which five wires were connected together and the four intermediate wires were connected to the second terminal of the raising transformer. Two wires at one end were then left off. Two of these were next omitted, leaving three connected to one terminal and two to the other. One of these was left off, leaving the 1st and 3rd wires connected together, and the 2nd and 4th also. The 1st and 9th wires were then connected together, also the 2nd and 8th. As the 1st and 2nd wires were well separated from the 8th and 9th, the mutual effect between them is negligible, so that the loss in this case may be considered as double that which would be obtained from the 1st and 2nd wires alone. The results of this measurement are plotted in Fig. 2. The points for both loss and current fall on a straight line and indicate that each additional wire causes a definite increase.

Measurements made upon wires at greater distances show that the action is considerably less as the wires are separated. The loss is approximately the same at 28,000 volts when the wires are 4″ apart that it is at 36,000 volts when they are 16″ apart. The loss for a distance of 8″ is intermediate.

Other measurements were made, but nothing of further importance was developed. It is interesting to note that within a few days of the first measurements the general characteristics of this loss were determined, namely, that the loss between wires increases rapidly after a critical voltage is reached, that the loss is practically independent of the frequency, that it is much less as the distance between wires is increased. When a loss of 1200 watts was obtained on a total length of 540 feet of wire at only 30,000 volts, the important bearing of this phenomenon upon

transmission became very evident. The tests were stopped as preparations were begun for the continuation of the work at Telluride.

Transformers At Telluride.

The original Telluride plants operated at 3000 volts. Both the generator and the synchronous motor were wound for this pressure. Two transformers were furnished for the high-voltage tests, one for raising the generator voltage for transmission and the other for lowering the voltage for the motor. The windings were connected with a number of terminals by which the high-

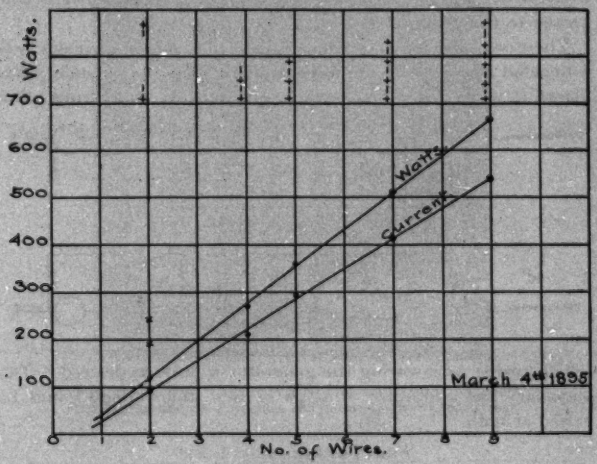


Fig. 2.

tension voltage could be varied over a wide range up to 60,000 volts.

Coils of similar shape were placed side by side in what is known as the "parallel" form of construction. Each coil had many layers of wire and but few turns per layer, thus securing a small difference of pressure between consecutive layers. The high-tension winding was divided into four similar coils, each designed to give a maximum of 15,000 volts. The individual coils could be differently connected, either in series or in multiple. The low-tension coils were five in number and were provided

with loops, by which the number of effective turns could be varied. Three low-tension coils were placed between two pairs of high-tension coils and the two remaining low-tension coils were placed on the two ends. Between the low-tension and high-tension coils metallic shields were placed, which were connected to the ground for protecting the low-tension circuit from danger in case of accidental contact with the high-tension circuit, and also for screening the low-tension circuit from electrostatic induction from the high-tension windings. The transformer was immersed in a case containing oil. The iron and the case of the transformer as well as the shields between the coils were connected to the ground.

There was also an auxiliary transformer whose primary was connected across the generator terminals while its secondary was placed in series with the circuit to the raising transformer, thus

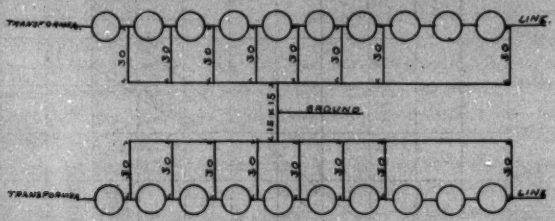


FIG 3.

either raising or lowering the generator E. M. F. as desired. The secondary had a number of steps so that the voltage could be varied at will.

THE TRANSMISSION LINE.

The line extends from the power station near Ames, which is a few miles from Telluride, Colorado, to the Gold King mill. The line passes over an exceedingly rugged country and has a total length of nearly 2¼ miles (11,720 feet). There are 62 poles, each carrying three cross-arms, the upper being about 26 feet from the ground. Each cross-arm carries two wires supported by insulators which are designated as follows:—Large glass, small glass, porcelain. (See Figs. 4 and 5). The large glass insulator is the same as that used on the circuit in the San Bernardino and Pomona plant. The total height is 5″ and the maximum diameter 5½″. The bottom of the insulator stands 1¼″

FIG. 4.—50,000 Volts on Large Glass Insulators (Upper Cross-arm) and on Porcelain Insulators (Lower Cross-arm.)

FIG. 5.—Insulators used in High-Tension Tests at Telluride.

above the cross-arm. The porcelain insulator is $4\frac{1}{16}''$ high and $5\frac{1}{2}''$ in diameter. The bottom is $3\frac{1}{16}''$ above the cross-arm. The small glass insulator is $3\frac{1}{2}''$ in height, $4\frac{1}{4}''$ in diameter and stands $2\frac{1}{2}''$ above the cross-arm. This insulator is triple petticoat; the other two insulators are double petticoat. The circuits were strung with galvanized iron wire 0.165″ in diameter, which is No. 8 B. W. G., and about No. 6 B and S gauge. Later the circuit on porcelain insulators was changed to No. 6 B and S copper wire 0.162″ in diameter. The measured resistance of one of the iron wire circuits was 66 25 ohms at —7 deg. C.

The Lightning Protection.

The lightning protection was laid out by Mr. A. J. Wurts, who previous to this time had spent some months at Telluride, determining the requirements for protecting the 3000-volt circuit. The protection consists of choke-coils and spark-gaps of non-arcing metal, as described by Mr. Wurts in his paper[3] before the Institute, March, 1892.

In each line ten choke-coils were placed. Unit arresters, each consisting of seven non-arcing metal cylinders and having six spark-gaps, were connected as is shown in Fig. 3.

Running Tests at Telluride.

The first tests were qualitative rather than quantitative. It was uncertain what phenomena might accompany the operation of a long line at high voltage, and the pressure which could be used on the insulators was a matter to be determined. The first thing was to find what would work; measurements could be made afterwards. A high voltage was placed on the transmission line, sometimes transmitting no power and at other times operating the 100 H. P. synchronous motor. In December 1895, the motor was operated at 25,000 to 33,000 volts for several days. In January 1896, 45,000 volts was used continuously for over a week, and beginning with the latter part of March a continuous run of 37 days was made at 50,000 volts. "Some very severe conditions of weather were encountered during this time, very high gales of wind prevailed, the air was filled with clouds of dust, part of the time the snow which fell was quite damp and during the last few days of the run there was some rain. At this voltage the wires were plainly visible at night and the characteristic hissing of high-tension currents could be heard

3 Transactions, vol ix, p. 102.

several hundred feet. No lightning arresters had been installed up to this time and the cause of the shut-down was damage to the raising transformer, caused by lightning. Lightning arresters were installed. The lightning season commenced about June 1st. During the latter part of June lightning discharges over the arresters were very frequent. At this time we were limited to a running voltage of about 34,000 volts, as there were not enough arresters to permit of increasing the voltage. No trouble whatever was had with the lightning protection. Discharges were frequently seen crossing the arresters and during two or three days in the early part of the season discharges occurred at intervals of a few seconds for several hours. Enough arresters were afterwards obtained to run at 45,000 volts, but the lightning discharges were much less frequent."

Some measurements upon the line were made by determining the power to the raising transformers when the lines were connected and when they were disconnected. These measurements showed that the loss due to the line is small, below 45,000 volts, but increases rapidly when about 50,000 volts is exceeded, and reached 16.4 K. W. at 59,000 volts. The results up to 52,000 volts are given in curve 2, Fig. 9. Curve 1 in this figure is the loss on the same circuit measured a year later by a different observer using a different method. At the maximum loss shown there is a difference of only 8 or 9 per cent. in E. M. F. for the same loss on the two curves.

The record of the operation of this line at 50,000 volts for over a month is of very great interest, as it is a practical demonstration of the feasibility of operating a line at 50,000 volts, a pressure four or five times as great as any which had been in general commercial use. Mr. V. G. Converse had been up to this time closely associated with this work. He had much to do with the design and construction of the high-tension transformers and insulators, tests upon losses in lines made at the Pittsburg laboratory and the tests at Telluride.

Measurements at Telluride.

The work at Telluride was then taken up by Mr. R. D. Mershon. The facilities for experimental work were increased and instruments were provided for carrying on the tests. Mr. Mershon found peculiar difficulties in making exact measurements of the power to the circuit. A wattmeter in the low-tension circuit of the raising transformer led to errors under the conditions which prevailed. Some very able and painstaking

work was displayed in detecting the error and overcoming it with the facilities at hand—and the facilities were none too plenty in the heart of the Rocky Mountains for making measurements which would tax the resources of almost any laboratory. The apparatus used introduced a disturbing influence in the circuit, which, however, could be measured and eliminated. On the other hand, a wattmeter for measuring power on a high-tension circuit must accommodate a very high voltage and a very small current. As the charging current to an open line is usually very large in proportion to the loss current, the error of the instrument is very sensitive to slight variations of phase in the shunt current. A description of the instruments and the methods used are given in an extract from the report of Mr. Mershon which will be found at the end of this paper in Appendix A. The results of the measurements and the conclusions are given partly by extracts from Mr. Mershon's report, and partly in abstract.

Results of Measurements.

"The results of measurements taken are embodied in curves.

"In every case the measurements were taken upon an open-circuited line—in no case upon a line which was transmitting power. The line losses obtained are therefore a combination of those occurring between the line wires and the very small $I^2 R$ loss in the wire itself due to the charging current of the line.

"Measurements taken with the Weston wattmeter include the loss in the high-tension coil of the power transformer due to the currents applied to the line. This loss is in general small and in the following curves corrections have not been made for it. Curves taken with the Thomson wattmeter require no such correction.

"There is an additional correction which may be made in the case of those curves whose voltages were obtained from the raising transformer. This correction arises from the fact that the action of the capacity current taken by the line, in connection with the series reactance of the transformer supplying it is such as to make the voltage impressed upon the line somewhat greater than that obtained by the ratio of the transformer winding. The measurements taken to determine the amount of the error in voltage show it to be small.

"There were two generators used. One was that regularly running and supplying power to the power circuits of the Telluride Power Transmission Company. It is a 600 K. W., 22-pole, quarter-phase machine, delivering 500 volts at a frequency of 60, or 7200 alternations per minute. Its armature is of the slotted type and is wound with copper bars. In the notes this generator is designated as 'Slotted Armature.'

"The other generator is one whose field is that of the 100 K. W. toothed armature machine, originally sent out as a part of the first Gold King transmission plant. It has twelve poles and as originally run operated at 3000 volts and 10,000 alternations. There are two armatures for this machine; a surface wound armature, designated as 'Smooth Armature,' and a toothed armature, designated as 'Toothed Armature.'"

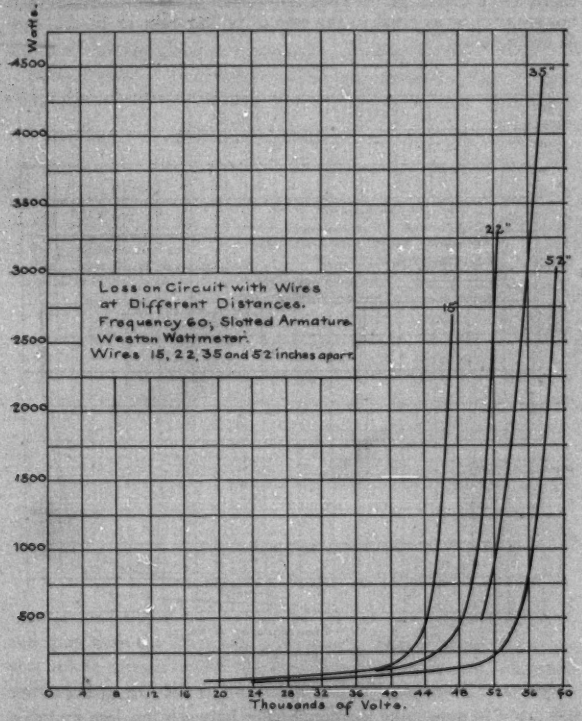


FIG. 6.

Comparison between Insulators.—A set of measurements was made for comparing the loss on the three circuits supplied respectively with large glass, small glass and porcelain insulators. The curves are very nearly identical and correspond very closely with the right hand curve in Fig. 6. "There was a heavy wet

snow on the ground and the cross-arms at the generating station and more or less snow all along the line; that at the further end being drier than at the generating station. There was more or less snow falling during the measurements, and this accounts for a wide variation of the points taken at the high voltages, as falling snow renders the wattmeter reading very unsteady, the unsteadiness being such as one might expect if from time to time there was a discharge between the wires. This unsteadiness does not seem to be as great in the case of falling rain as in the case of falling snow"

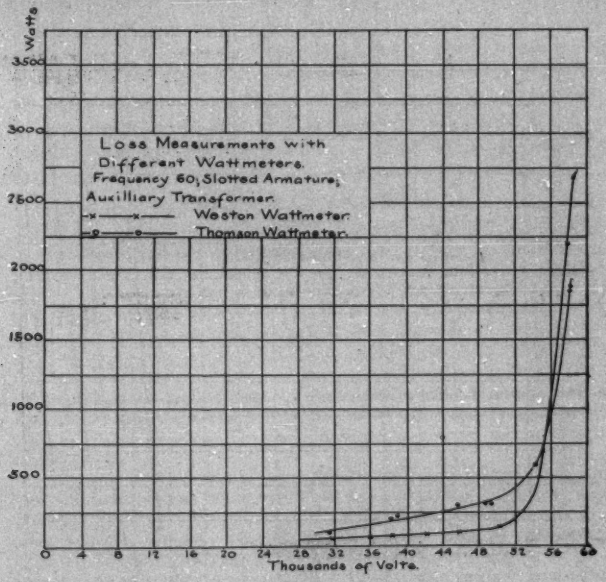


FIG. 7.

Loss and Distance Between Wires.—A series of measurements was made to determine the connection between the loss and the distance between wires. "As at that time it had not been fully demonstrated that the loss was not affected by weather conditions except there was precipitation, changes in distance between wires were made upon one circuit, while the distance between wires on another circuit was maintained always the same, and the latter was used as a reference circuit when a change in loss was obdinate."

The several curves have been plotted together, due correction being made for the slight difference in the loss in the reference circuit, which probably resulted from slight differences in the precipitation when the curves were taken. The distance between the wires in the several tests was 15, 22, 35, and 52 inches respectively. The results are shown in Fig. 6. It will be noted that the loss is much greater when the wires are close together and that the curve begins to ascend at a lower voltage.

Comparison of Wattmeters.—The loss curves in Fig. 7 were taken on one of the circuits, first, with the Weston wattmeter

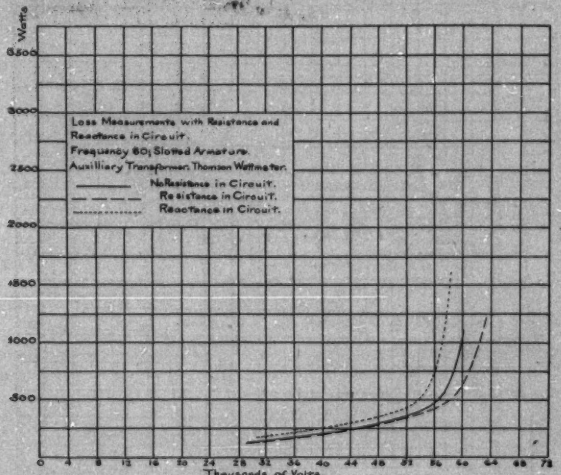


FIG. 8.

and then with the Thomson wattmeter. The Weston wattmeter was not in circuit when the measurements with the Thomson wattmeter were taken. As an additional check, the readings were taken on each of the wattmeters of the loss occurring in the shunt resistance, of the Thomson wattmeter the results were in practical agreement with each other and with those obtained by calculation. The discrepancy in the results obtained on the two instruments when measuring line loss will be referred to later.

Loss on Insulators.—A set of comparative readings was taken on one of the circuits and on a dummy circuit, identical with the

main circuit, as regards kind and number of insulators and the size of wire, but only 60 instead of 11,720 feet in length. The results show that the loss on the two circuits is practically identical up to about 50,000 volts, which is the part of the curve below the bend. The losses agree closely with those shown in Fig. 6. At higher voltages the loss on the dummy circuit increased slightly, indicating that the loss was of the same nature as that at a lower voltage. The agreement of the loss on the two lines

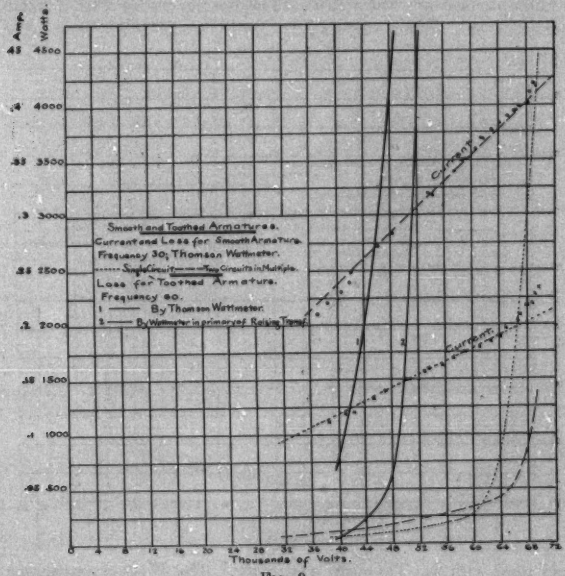


FIG. 9.

at low voltage (*i. e.*, below the bend in the loss curve) indicates that this loss was over the insulators. The great increase in loss on the long line at high voltage indicates that the loss was due, not to the insulator, but to the line.

Resistance and Reactance in the Circuit.—Measurements were made with resistance between the generator and the raising transformer, then with reactance and then with neither resistance nor reactance. The results are shown in Fig. 8, and indicate a

different condition, depending upon the character of the circuit supplying the current. It was presumed that this difference arose from a modification of wave form of the E. M. F. applied to the line.

Wave Form and Loss.—Measurements were made upon the wave form and the corresponding losses when different generators

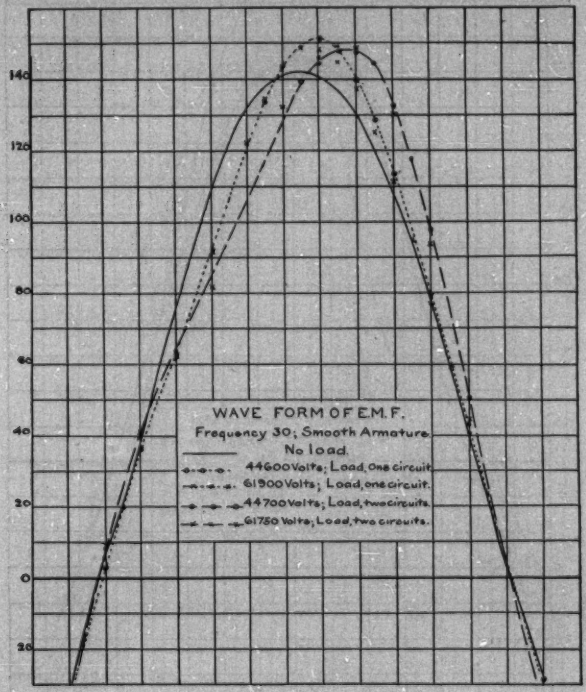


FIG. 10.

were used and different circuits were connected. In one test an armature giving nearly a sine wave was used which delivered current at 30 cycles. Measurements were made upon one circuit only, and then upon two circuits in multiple. The current and the loss are both given in Fig. 9. The wave form for no load and for both conditions of load are given in Fig. 10. The cur-

rent taken by the two circuits in multiple is twice that to a single circuit. The variation from a straight line in one of the current curves is due to a change in wave form as the voltage is increased.

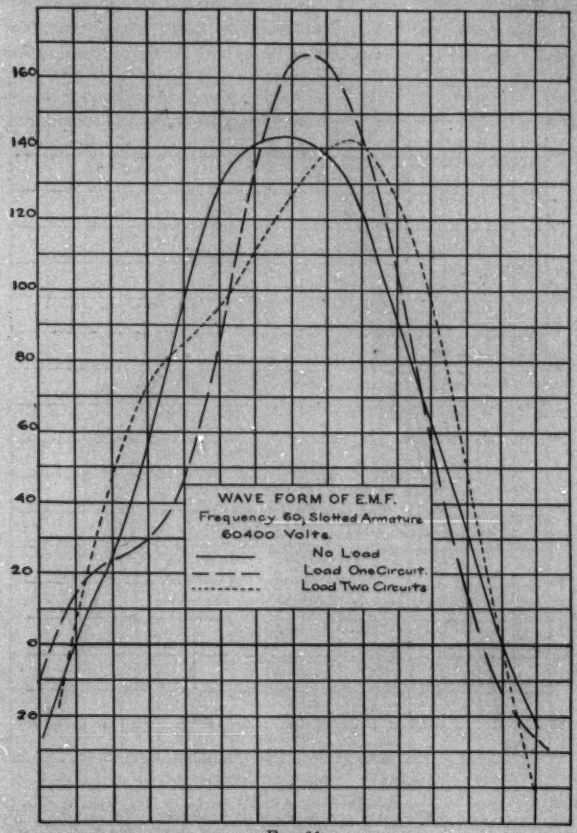


FIG. 11.

The loss for the two circuits in multiple is about twice as great as for one circuit at low voltages, but it is less than that for one circuit at high voltages. Referring now to the wave form taken

at high voltage, it is seen that the wave form for the two circuits in multiple has a lower maximum than that for one circuit alone. The reduced loss on the two circuits is undoubtedly due to the different wave form when both circuits were connected. The distortion of the wave form is due to the reaction which the leading current produces in the generator and transforming apparatus.

Wave forms were also taken on the slotted armature giving 60

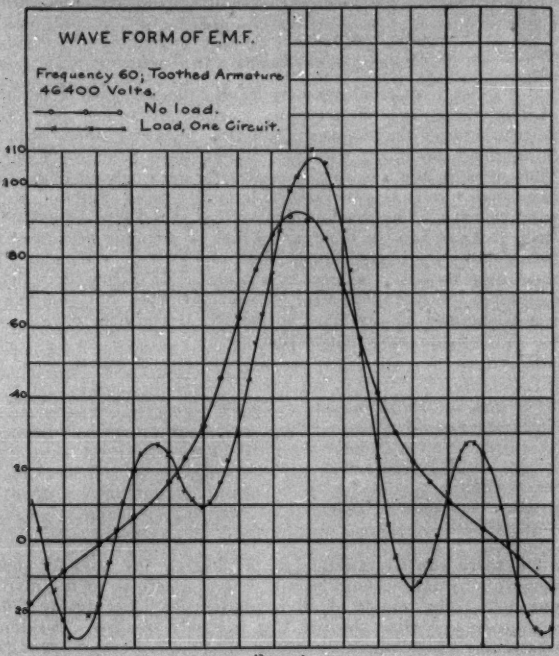


FIG. 12.

cycles. The wave forms are given in Fig. 11. The conditions are similar to those just described, in that a single circuit produces a wave having a much higher maximum than that produced when two circuits are run in multiple. The losses (which are not shown) bear the same general relation as that in the last case, namely, the loss with two circuits is greater at low voltage and at the high voltage is less than that on a single circuit.

A wave form was taken upon the toothed armature both at no load and also when supplying current to one of the circuits. These are shown on Fig. 12. This wave differs radically from a sine wave at no load and is greatly distorted when supplying a leading current. In the no-load wave the value of the fundamental is 72.5 per cent.; the third harmonic 21.6 per cent.; the fifth harmonic 4.8 per cent. The corresponding loss is given in Curve 1, Fig. 9. The distorted wave makes the Thomson wattmeter read too high, especially at the lower E. M. F's.

Other Observations and Tests.

"A series of observations were taken extending over a period of thirty-three days, to determine whether there was any connection between the loss occurring on the lines and the variations in weather conditions. Three readings were taken each day. They were, in addition to the wattmeter readings, readings for barometric pressure, temperature, humidity, wind direction and wind velocity. The weather observations were taken simultaneously at Ames and the King, using sets of weather instruments furnished by the United States Weather Bureau. The range of these observations is shown in a table given below, in which maximum and minimum refer to the maximum and minimum results obtained at any time during the thirty-three days over which the measurements extended:—

Location.		Barometer.	Temperature Deg. F.	Humidity per cent.	Wind velocity miles per hour.
Ames.	Maximum.	22.19"	73.5	43.2	22
	Minimum.	21.68"	56.3	7.1	2
King.	Maximum.	21.82"	62.0	42.5	30
	Minimum.	19.81	47.8	3.0	3

"If there was any variation in the loss on the lines for this range of weather conditions, it was so small as to be inappreciable. The results of all measurements taken during this work seem to confirm the fact that the only weather condition whatsoever which affects the loss to any practical extent is that of precipitation. The loss seems to bear some relation to the size of the particles precipitated, being greater for a fall of snow in which the flakes are large than one in which the flakes are small.

"In the power transformers used, the series reactance was comparatively small because of the subdivision of the coils. A change in the condition on the line as regards loss occurred when the Weston wattmeter was placed in circuit. This was detected by measurement upon the Thomson wattmeter, both when the

Weston wattmeter was in circuit and when it was not. Moreover, the lines hissed when the voltage is 55,500 and the Weston wattmeter is out of circuit, but when the Weston wattmeter is thrown into circuit the hissing ceases, although the voltage rises to 57,700. The hissing sound is a characteristic of high-voltage lines and begins at the bend in the loss curves. It always accompanies luminosity of the lines.

"Along with this change there was another phenomenon not previously mentioned. This was a discharge which took place from time to time between the terminals of individual choke-coils. The discharge would occur sometimes between the terminals of one choke coil and sometimes simultaneously on two or three of the choke coils. These discharges made considerable noise, sounding very much like a pistol shot, and could be heard at a considerable distance from the transformer house. As the choke-coil terminals are distant from each other about 8½", it is not thought that this discharge took place through the air, but over the surface of the wood enclosing the choke-coil. The discharge, however, left no mark on this surface. Simultaneous with these choke-coil discharges one could hear, if standing under the line some little distance from the transformer house, a slight snap which seemed to be a phenomenon rather of the whole line than of any particular spot in it. Sometimes there was a corresponding snap over the lightning arresters. As the lightning arresters make more or less noise at all voltages, this snap over them may have been present at all times, but in some cases not sufficiently well marked to be heard above the continued hissing of the lightning arresters.

"After the preceding results had been obtained, the two power transformers were connected up with their high-tension windings in series, the point of connection between them being grounded, and with their low-tension windings in multiple. With this arrangement voltage was impressed on one of the circuits, power being supplied by the smooth armature at 7200 alternations. The voltage was run by means of the machine field to 90,000.

"As the power taken by the lines at this voltage overloaded the motor used to drive the generator, a span was cut out of the circuits at a little distance from the station, leaving about 500 feet of wire in them. The voltage was run up to 133,000 volts and held there for some minutes; but the current finally jumped from the outside terminal of each transformer to the iron, smashing the heavy glass tube with which these terminals were insulated."

Discussion of Results.

The following is taken from Mr. Mershon's discussion of the results of his tests:

"There is evidently a certain critical voltage at which the loss occurring between wires begins to increase very rapidly; indeed,

it seems as though there might be something of the nature of a polarization similar to that which occurs in the case of an electrolyte; that there is something of this nature in the case of air or other gases subjected to an electrostatic stress is well known, and it has been taken as an explanation of the fact, that in the experimental determination of sparking distances in air, a certain minimum potential is necessary to establish an arc, no matter how small be the sparking distance. Also, Varley has done some work on tubes containing gases. This work was done with a series of Daniell's cells yielding 300 to 400 volts. The voltage was impressed upon electrodes sealed into the tubes. He established the following facts:—First, that each tube required a certain potential to leap across; second, that the passage for the current having been once established a lower potential was sufficient to continue the current; third, if the minimum potential which would maintain a current through the tube be P and the voltage varied to P plus 1, P plus 2 etc., to P plus N, the current will vary in strength as 1, 2, 3, etc., N; P always meaning the lowest value at which the current will continue, and is less than that at which the current starts.

"If such a condition of affairs obtains in this case, the loss curves of the preceding sheets must be made up in two parts, one the loss over the insulators and cross-arms, the other the loss occurring through the air. The first part of the loss curve up to or near the point where the abrupt bend begins, must be the loss over the insulators and cross-arms alone; beyond the point where such a bending occurs, the loss curve must be made up of a combination of the two losses referred to.

"If the action which takes place in air is similar to that obtained by Varley, we might expect that both (1) the position of the critical bend on the loss curve and (2) the law which the loss follows above the bend, would be affected by the form of the E. M. F. wave impressed upon the line for the former (1) must depend, not upon the mean square of the voltage impressed upon the line, but upon the mean square of that portion of the E. M. F. wave which is above a certain critical voltage, and the latter (2) must depend upon the form of that portion of the E. M. F. wave above a certain critical voltage because, as Varley shows, the minimum voltage at which this peculiar loss begins, differs slightly from the minimum voltage at which it will continue after the action has been established. If it were not for the latter consideration it would be comparatively easy to determine the equation for such loss at least in the case of a pure sine wave, and it might be that there is a sufficiently small difference between the voltage at which this loss will begin and the voltage at which it will discontinue for such an equation to hold practically. That the loss depends upon the maximum value, if not upon the form of the E. M. F. wave, is shown by several of the loss curves in connection with their corresponding wave forms. This is particularly

noticeable in one or two cases where the loss on two lines in multiple is less than that on one line, and although some of these comparisons will have to be made between curves taken on the two different wattmeters and are, therefore, not strictly comparable, they may be compared after such correction as is mentioned below in discussing the wattmeters. In any case the curves are comparable, qualitatively, as regards the position of the critical point.

"It might be objected that the results are rendered questionable by the curves in Fig. 7. The curves were taken under presumably similar conditions, except that one was obtained by means of the Thomson wattmeter and the other by means of the Weston wattmeter. This discrepancy is attributed to a charging current passing through the shunt resistance of the Thomson wattmeter. That the amount of capacity current necessary to produce the discrepancy is small, appears upon the following considerations:—In one case the loss obtained upon a circuit at 38,000 volts when using the Weston wattmeter is 90 watts, and under the same conditions, but using the Thomson wattmeter, the loss is 215 watts. The difference in the loss obtained by the two wattmeters is therefore 125 watts. The current is about 0.25 of an ampere. Now, 0.25 of an ampere if in step with the E. M. F. would give on the Thomson wattmeter at 38,000 volts a reading of 9500 watts; therefore the capacity current through the shunt resistance necessary to produce the discrepancy of 125 watts is 125 divided by 9500, or about 1.3 per cent. of the current in the shunt resistance. The shunt resistance has a value of 1,202,300 ohms; at 38,000 volts the current through it would be about 0.032 amperes; 1.3 per cent of this, or 0.00416 amperes is that required to produce the discrepancy noted. In further support of this method of accounting for the discrepancy, the results obtained at different numbers of alternations using the Thomson wattmeter show a variation for different numbers of alternations of the losses below the bend in the loss curve, and which are thought to occur over insulators and cross-arms. There should be no variation in such loss for a variation in frequency.

"Any discrepancy occurring in the Thomson wattmeter by reason of a capacity current in its shunt resistance will be affected to a greater or less extent by change in the wave form.

"It is believed that all the phenomena connected with this work may be studied in a tube which has been partly exhausted. The work could then be done with comparatively low voltage and using direct current which would much simplify the measurements. The contents of the tube might be partially rarefied air or other gas, as the action would undoubtedly be similar in all gases. With such a tube might be studied the law of variation in distance and form of electrodes, also in material and surface of the same.

Resumé and Conclusions.

"It is undoubtedly true that the loss is made up of a loss over insulators and a loss between wires, and that the latter is the only loss worth considering.

"The loss between wires is not affected by any atmospheric conditions except precipitation. This statement of course must be taken as applying to such a climate as that in which the measurements were taken. The lines were seldom in fogs or clouds, and when they were, or when rain was falling, the moisture was of the purest. Near cities the loss would be undoubtedly much greater than that shown in these curves, because of the impurities both in solution in the moisture of the atmosphere and in suspension.

"There will be for a given transmission a certain economical voltage, because while an increased voltage, with a given line wire, will reduce the loss in this wire by decreasing the transmission current it will also increase the loss between the wires.

"It is believed that attention to wave form is very important. The sine wave is undoubtedly the best as giving a stable form, and because of superior results with all kinds of apparatus. A flat wave would of course give less loss, but would not be stable, and as the nearest practical approach to a sine wave will not be perfectly stable but will still contain some harmonics, it will be of advantage to keep the series reactance of the transformers and generators as low as possible.

"It is believed that 40,000 volts is perfectly conservative and safe as regards loss between wires for any ordinarily good wave form, and in a climate such as that in which the measurements were taken, *i. e.*, where the air and precipitated moisture are practically pure, 40,000 volts comes well below the bend in the loss curve even under the worst weather conditions.

"I can see no advantage of porcelain over glass, unless it be that of superior mechanical strength. The latter is rather a doubtful advantage. The ball from a heavy calibre rifle or revolver such as are used in the western country will smash any insulator whether glass or porcelain. Porcelain offers a more tempting mark, being white. As to hygroscopic properties, no difference could be discovered so far as these measurements were concerned. It will make little difference under running conditions whether the insulator be hygroscopic or not, as the small amount of power necessary to keep the surfaces dry will be insignificant. I say under running conditions, because in starting up a 'cold' line there is danger of break-down if current is put on suddenly at full value, instead of being raised gradually. As far as the resistance to piercing is concerned, glass is just as good practically at least as porcelain. It needs no electrical test to pick out a good glass insulator, which is one advantage of glass over porcelain.

"To sum up, glass insulators are cheaper, lighter, more easily tested and less likely to be shot at than porcelain; on the other hand, they have less mechanical strength.

"In every case, in my experience, where a breakdown has occurred, it has been on a cross-arm which was 'wind shaken' and 'weather cracked,' the current following the cracks. This leads to a curious result. The mark of the current will be on surface of the arm for five or six inches, then disappear from the surface altogether for some inches, then reappear, etc. On cutting open the arm one sees how the current has followed the best path, dodging in and out. Rain and moisture probably settle towards the cracks, carrying salts from the body and surface of the wood. This forms a path of low resistance, especially in wet weather. For this reason I have in the plant of the Colorado Electric Power Company taken particular pains in treating both pins and cross-arms. The cross-arm treatment is such as fills all cracks and fissures as a section of the wood shows.

"This report would be incomplete without an acknowledgment of the assistance rendered in the work by the engineering force of the Telluride Power Transmission Company, headed by Mr. P. N. Nunn. Especial credit should be given Mr. A. L. Woodhouse for his faithful work and constant perseverance in the face of great discouragement."

High-Tension Tests at East Pittsburg.

Laboratory tests and measurements on a small scale cannot take the place of tests under the conditions of practical service, such as those at Telluride. There are, however, many important elements which may be determined by laboratory measurements.

A high-tension line for testing insulators and making measurements upon the losses between wires was erected at the East Pittsburg factory in the fall of 1897. A number of the tests which have been made are here recorded.

(1) A test was made to determine whether the wave form of the charging current to the line was similar to that through a resistance, or whether it was modified by the loss component, the loss occurring only at the higher part of the E. M. F. wave. The current to the high-voltage line, at pressures varying from 30,000 to 60,000 volts, was passed through a coil possessing high self-induction. The E. M. F. upon the coil was measured by a voltmeter. The E. M. F. was also measured when a current of equal strength was passed through the coil, the line being short-circuited and a low E. M. F. applied. It wasfound that the voltage upon the coil was the same, within a small error of obser-

vation, in both cases, showing practically no difference in the wave form of the current under the two conditions. The current was from an armature giving practically a sine wave.

(2) The charging current to the line was measured under several different conditions when the current was obtained from a generator giving practically a sine wave. The results of measurements were compared with the currents as calculated by the theoretical formula. The last measurement in the table was made upon the Niagara-Buffalo line, with current from a Niagara Generator, which differs slightly from a sine wave.

COMPARISON OF MEASURED AND CALCULATED CHARGING CURRENT TO PARALLEL WIRES. LENGTH, ONE MILE—10,000 VOLTS.

Size of Wire.	Distance between Wires.	Frequency.	Measured Current.	Calculated Current.
No. 8 B and S	21.7″	60	.0307 Amperes	.028 Amperes
8 B and S	48.0″	60	.0245 "	.0252 "
8 B and S	79.5″	60	.0234 "	.0238 "
8 B and S	127.5″	60	.0225 "	.0222 "
No. 8 and ground	120.0″	60	.0427 "	.0412 "
0.71″ diameter	18″ for 2/3 of distance 36″ " 1/3 " "	25	.0176 "	.0176 "

A table giving the calculated charging current for a number of conditions will be found in Appendix B.

(3) The fall of potential around the wires was noted by tests made with spark-gaps. The wires 48″ apart were connected to the high-voltage terminals and a spark-gap was placed between two idle wires also 48″ apart, placed about 21″ below the first wires. A spark-gap consisting of brass terminals with a $\frac{1}{4}$″ radius was placed between the two idle wires. When the gap was $\frac{1}{32}$″ the sparking began when the E. M. F. from the raising transformer was 26,000 volts. A gap of $\frac{1}{32}$″ requires an E. M. F. of 2,200 volts to produce sparking. When the spark-gap was made $\frac{8}{32}$″ (equivalent to 12,000 volts) the sparking began at 103,000 volts from the raising transformer. At intermediate points there is a fair proportionality between the spark-gap and the E. M. F.

In another test a spark-gap was placed between one of the idle wires and the adjacent wire of the live circuit. When the spark-

gap was $\frac{1}{8}''$ (equivalent to 6,000 volts) the spark passed when the E. M. F. was 17,500 volts, and when the spark was made $\frac{1}{4}''$ (equivalent to 12,000 volts) the sparking began at 33,000 volts. When the gap was $\frac{3}{8}''$ (equivalent to 16,000 volts) sparking

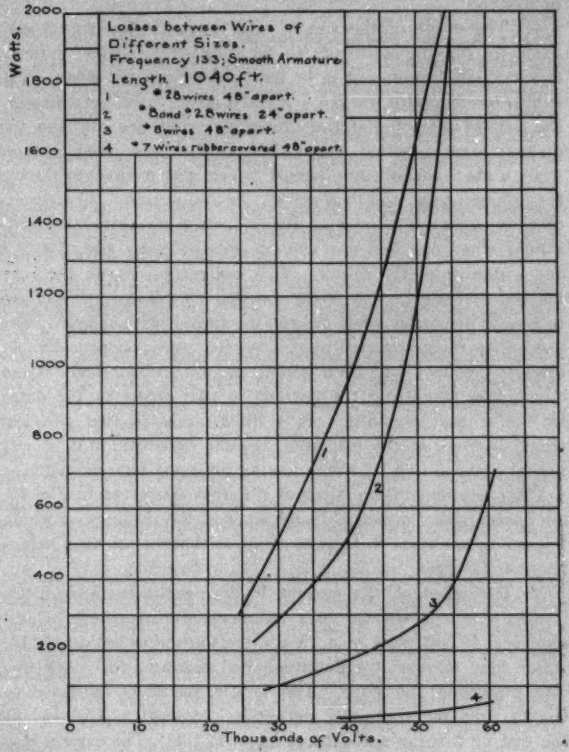


FIG. 13.

began at 41,000 volts. When the gap was $\frac{1}{2}''$ (equivalent to 20,000 volts) sparking occurred at 49,000 volts. The E. M. F. did not differ greatly from a sine wave. These tests have an important bearing in connection with the running of telephone and

other circuits adjacent to high-potential wires. It is essential that the wires of a high-potential circuit be spiraled so that each wire sustains the same relation as every other wire to the second circuit, in order that the effects of static induction may be neutralized.

(4) The effect of the size of wire upon the loss was investigated by running a pair of No. 28 brass wires 0.0126″ in diameter and then replacing it by large rubber-covered wires. The rubber-covered wire was No. 7 B and S. gauge 0.144″ in diameter; the outside diameter of the rubber covering was 0.3″ and the diameter over the braid was 0.35″. In each case measurements were made upon another circuit which was unchanged during the different tests, and thus served for comparison. The results of these tests are shown in Fig. 13, which also gives the conditions when one fine wire and one wire of larger size, No. 8 B and S, constituted the circuit. This comparison shows the very marked increase in loss when the fine wire is used. The loss is greatly decreased when the rubber-covered wire is used. The loss on the rubber-covered wire, however, increased considerably after the voltage had been raised and the rubber had broken down, thus permitting the current to pass freely to the outer surface of the insulation. It is quite probable that the loss would increase as the insulation became defective, until it was nearly equal to that of a wire having the same total diameter.

The measurements on wires of different size given in Fig. 13. are qualitatively correct, although some of the readings on which the curves are based were quite small, so that the absolute values may not be exact.

(5) The effect of the current in drying the surface of the insulators was illustrated in a test made during a rain. Upon applying 45,000 volts to a circuit the wattmeter indicated 116. After four minutes the deflection had decreased to 72, the current remaining the same. The E. M. F. was then increased to 60,000 volts, the wattmeter deflection increased to 155, and at the end of three minutes it had fallen to 138. The current was one-third greater than at the lower voltage, but remained constant while the wattmeter changed. The rain continued during the test, which shows, therefore, that the condition of the insulator is materially improved by the presence of the current.

(6) It was noticed that when there was a break-down upon the line and the current passed suddenly between wires over the

surface of the cross-arm that there was a sparking between the terminals of the ammeters in the high-tension circuit across the surface of the instrument. This was further investigated by placing in circuit a coil of low resistance through which one ampere would be sent by about 1½ volts at a frequency of 125. A spark-gap was placed in shunt to this coil. A 2″ spark-gap was also placed between the line wires. The voltage of the primary was gradually raised until at 35,000 volts the current passed across the spark-gap between the line wires. A spark also passed across a gap of ⅜″, shunting the small choke-coil. This test shows the remarkable suddenness of the rush of current when the short-circuit occurs due to the breaking down of the spark-gap on a high-voltage circuit. This phenomenon was observed by Mr. Mershon in choke-coils used in connection with lightning arresters at Telluride.

Running tests were made on four lines in multiple at high voltages. Each line consisted of two wires 1,040 feet in length held by 26 insulators. The insulators were of various types of glass and porcelain, some of the ordinary form and some underhung. For hours at a time 100,000 volts or slightly more were kept upon the line. For about six weeks voltages ranging from 70,000 or 80,000 to 100,000 volts were kept on the lines for about eight hours a day. When there was rain the line would short-circuit and the voltage had to be reduced. During a driving rain storm 48,000 volts was kept on the lines, and it may have required a considerably higher voltage to have caused short-circuiting.

(7) A high-tension wattmeter similar to the Thomson wattmeter at Telluride was used. To correct the wattmeter for the errors caused by charging current in the shunt resistance, a condenser was placed in parallel to the shunt circuit of the wattmeter. This condenser should be so adjusted that the current through the shunt circuit of the wattmeter is the same that it would be if there were no condenser and the shunt resistance had no capacity. This permits the capacity current in the circuit to be shunted round the wattmeter by the condenser. The condenser in shunt to the wattmeter was capable of adjustment, and by varying its capacity the deflection could be made positive or zero or negative when current was delivered to a constant load. The proper adjustment was made by taking a comparatively low voltage, at which the charging

current was very high in comparison with the loss, so that the loss was nearly negligible, and adjusting the wattmeter to indicate zero. At higher voltages, when there was a considerable loss, the error with this adjustment would be inappreciable. Certain variations with temperature and humidity were noted which would be explained by a variation in the capacity of the resistance, causing a variation in the charging current to the shunt circuit of the wattmeter. The high resistance for the shunt circuit was wound upon fuller-board plates containing brass stiffening pieces. Tests were made upon individual plates by measuring the capacity between the wire and the supporting strip of brass, and it was found that the capacity and the insulation resistance both varied with the amount of moisture in the fuller-board insulation. In order to prevent variations of this kind, subsequent resistances were wound upon glass plates, which seems to be a very satisfactory form of construction.

Tests at Niagara.

Some measurements have been made upon the Niagara-Buffalo transmission line. There are two circuits of three wires each, one of which was in service and the other was available for tests. Each circuit consists of three cables each of 350,000 c. M., approximately 0.7″ in diameter. The cables are run on porcelain insulators, and are on the same cross-arm. Adjacent insulators are 18 inches apart and the circuit is spiraled, so that each of the three wires occupies the middle position for a third of the distance. Current from one of the 5000 H. P. generators was applied to the line through a raising transformer, by which the voltage can be increased by small steps to 100,000 volts. This transformer is part of a high-tension testing outfit which is described by Mr. C. E. Skinner in the *Electrical World*, March 5, 1898. The wattmeter is a Thomson inclined coil instrument with a high resistance shunt of german silver wire wound on glass plates. The ammeter is a Thomson inclined coil instrument, connected directly in the high-voltage circuit.

Measurements were made between the various pairs of wires, *i.e.*, 1 and 2, 2 and 3 and 1 and 3; the current was found to be practically the same in each case; the loss on one of the circuits was slightly greater than that on either of the other two, on which the losses were about equal. The accompanying curve shows the measurements of current when two wires were connected

and the measurement of loss; the latter measurements were made upon one pair of wires up to about 26,000 volts and then upon a second pair. The results are given in Fig. 14.

On another day measurements were made of the resistance between each wire and the ground, and corresponding measurements

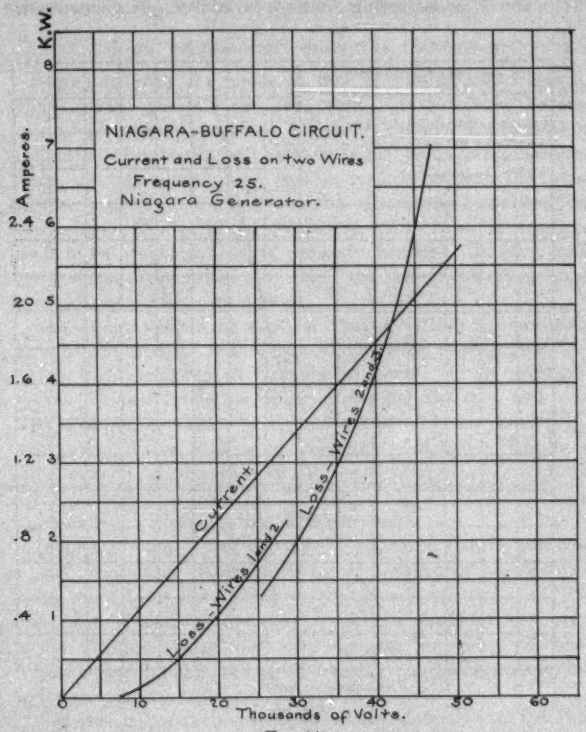


FIG. 14.

of loss were made by placing the high potentials between each wire and the ground. The measured loss was somewhat greater than the loss calculated by using the E. M. F. and the measured resistance. In these measurements, at voltages from 13,000 to 23,000 volts, the power factor calculated from the current and

wattmeter measurements, varied from about 4% to 6%, so that a very small charging current in the wattmeter would produce a considerable error in the reading.

Some measurements were made upon a pair of fine wires, in which the wires were placed at different distances apart. No. 31 B and S gauge spring brass wire 0.0089″ in diameter was

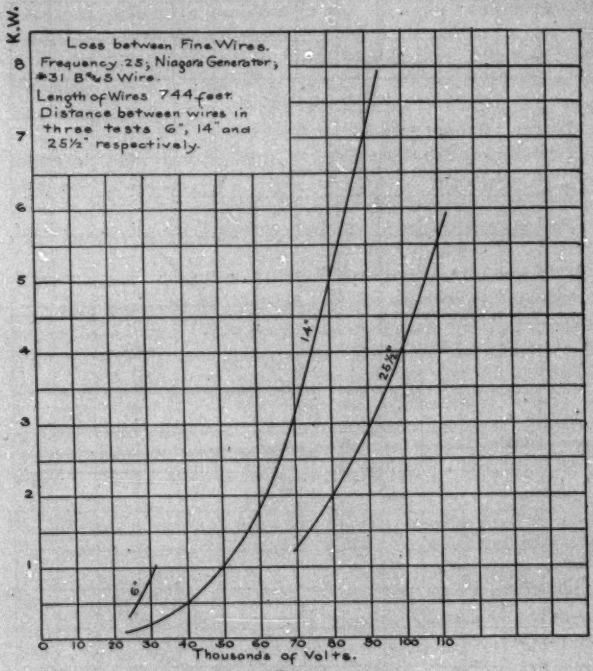


FIG. 15.

used. The length of the parallel wires was 744 feet. They were suspended by light strings successively at 6″ apart, 14″ apart, and about 25″ apart, the distance varying from 24″ to 27″. The wattmeter readings are given in the curves in Fig. 15. The power factor of the measurements made above 100,000 volts is about 95%, and is over 80% above 70,000 volts. There

can be but little error in the wattmeter due to charging current in the resistance at these power factors.

The measurements on the Buffalo line were made by the writer. Those on the fine wires were made by Mr. E. M. Tingley, who conducted the tests at East Pittsburg, and rendered valuable assistance in the preparation of this paper.

Power Transmission Plants in Operation.

Beginning with the plant at San Bernardino and Pomona, which began operation in 1892, using 10,000 volts and transmitting 30 miles, a constantly increasing number of plants have been installed operating at 10,000 or 15,000 volts. In some cases there has been little or no trouble experienced with the transmission lines, while in other cases the experiences have been less satisfactory. The principal trouble seems to have been a poor grade or an insufficient size of porcelain insulator. In other cases the insulators, sometimes porcelain and sometimes glass, have given almost perfect satisfaction.

The superintendent of a power company which has been running fifteen months with about 15,000 volts, reports that they "have had absolutely no trouble whatever of an electrical nature." Some insulators were broken because they had been used as targets by small boys or hunters, but only the outer petticoats were broken, and no short-circuits occurred, although in some cases insulators were in use for months with most of the outer petticoats chipped off. The distance of transmission is twelve miles. Porcelain insulators are used.

In another plant which has been in operation about a year and a half employing 15,000 volts for a distance of nearly thirty miles, there have been but three shut-downs on account of line difficulties. These were due to the breaking of insulators at a point where the line was spiraled. In one case the repair was made in half an hour, and in the other case a few minutes interruption to the service was sufficient for repairs.

The line is regularly patroled, and if a defective insulator or pin is found, the generating station is notified by telephone and the line is shut down for a few moments at noon. In one case two poles were burned by a defect in the insulators on the top of each. The poles burned to the ground, leaving the line hanging clear without any one at either the generating station or substation being aware of the fact.

Troubles have arisen on some lines by the burning off of pins by the passage of sparks from the outer edge of the insulator to the pin. These sparks make small holes in the pin no larger than a needle point, but after continuous sparking for some time the pin becomes entirely charred. An iron pin suggested itself as a remedy, but additional strains and liability to breakdown are liable when a conductor is placed within the insulator. The burning off of pins has occurred where small porcelain insulators are porous and the outside glaze is imperfect, while the glaze on the inside is good. When the porcelain is filled with water the current readily passes through it to the lower rim of the insulator and then sparks across to the pin. In one place which has been running for about three years some 250 pins burned off. The early insulators have been replaced by larger and better ones, and this defect has disappeared.

A 10,000 volt-line which runs for a dozen miles or more within a few hundred yards of the Pacific coast has burned cross-arms on nearly every pole. The cross-arms near the ends of the line, which are away from the coast, are not burned. Usually the burning appears as a mere blackening of the cross-arm for a short space between the insulators, on one side of the arm. In some cases the charring is deeper, and appears on both sides. The side on which almost all of the burning occurs is the one toward which the winds come from the ocean, bearing the mist of salt water. The wire shows discoloration, and the iron braces for holding the cross-arms are in a few cases eaten through. Moreover, the cross-arms were green and full of sap when erected. The early porcelain insulators were porous, and have now been replaced, and the pins are of iron. The charring has ceased almost entirely since the new porcelains were put up.

It may be observed that in the plants which are herein referred to and in the experimental tests, no mention has been made of insulators with cups containing oil for reducing the surface leakage. Insulators of this kind were used in the Frankfort-Lauffen experimental transmission line at 30,000 volts. Practically, however, the surface insulation is adequate without oil cups and the principal duty of the insulator is to prevent the current passing over the surface and jumping to the pin or cross-arm, a matter with which the oil would have nothing to do.

Telephone lines are in use in a number of plants placed on the poles which carry the transmission wires. The telephone lines

are usually placed some distance below the transmission wires and are crossed at frequent intervals. The telephones in general work very satisfactorily.

There appears to be practically nothing in power transmission in Europe using high potentials outside of Switzerland. The installation in Paderno in Switzerland is operating at 15,000 volts, the highest voltage which has been used in that country. The damp weather is one of the limiting factors. The insulators used are porcelain with a triple petticoat.

40,000 Volts in Commercial Service.

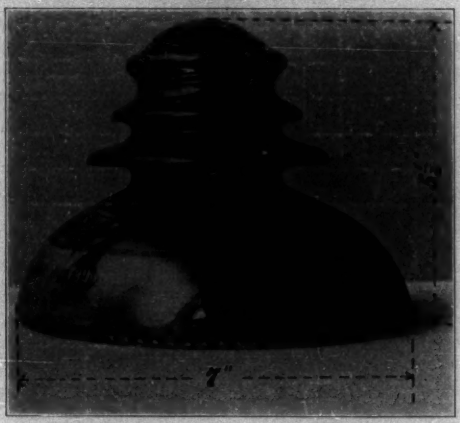


Fig. 16.—Insulator used at Provo for 40,000 volts.

The highest voltage which is used for transmission is in the Provo plant of the Telluride Power Transmission Company in Utah, which transmits power 35 miles to the Mercur mills at 40,000 volts. Raising transformers are three in number and are connected in the star form. Each transformer has a capacity of 250 K. W. The middle points of both the high-tension and low-tension circuits are grounded. In general design these transformers resemble the transformers used in the high-tension tests at Telluride; the design and construction having been under the direction of the same man in both cases. The line extends

from Provo at an elevation of 4,500 feet to Mercur, at 2,000 feet above Provo, and the line reaches an extreme height of about 10,000 feet above the sea level. Three miles of the line are strictly mountain construction. The lightning protection is afforded by choke-coils and Wurts non-arcing metal arresters. The insulators are of glass. The design was based on the tests at Telluride and they were made especially for this plant. The form is shown in Fig. 16. The insulators are held on special pins of oak which are thoroughly paraffined. The lower part of the insulator is 5″ above the cross-arm.

In dry weather there has been no difficulty whatever in operating. The insulators do their work as effectively as could be ex-

FIG. 17.—Insulator used by Colorado Electric Power Company for 20,000 volts.

pected if the voltage were only a few thousand volts. When everything is dry, the line will operate without difficulty, even if some of the insulators are off and the wire rests upon the cross-arm. When it rains there is sometimes trouble. It is indicated in the station by the ammeters giving quick swings, showing momentarily strong currents. Sometimes this is apparently a short-circuit and blows a fuse. In every case when there has been trouble on the line it has been in rainy weather, and broken insulators have been found which located the trouble. It is certain that in most cases these have been previously broken by bullets, and in other cases it is probable that the insulators were likewise broken. It is believed therefore that had there been no intentional break-

age of insulators there would have been no trouble upon the line since the plant began operating in February last. A few of the insulators near the station are not far from the overflow and are in a moisture equivalent to a rain all the time without doing any damage. Snow has often backed from the cross-arm up against the bottom of the insulator and around the first petticoat. It is usually found that the part of the insulator around and near the wire does not receive deposits of moisture or frost but remains dry, the particles being repelled. At this plant, current for about 700 H. P. is carried through three fuses of copper wire 0.01″ in diameter. Iron wire is used on a branch line for transmitting about 100 H. P. for about 3 miles.

This plant has been in operation in winter and in summer, "in thunder, lightning or in rain," the sole supply of power for the enormous De Lamar mines and mills, at Mercur, and is a happy and fitting consummation of the high-tension tests described in the beginning of this paper.

Limitations of High-Voltage Transmission.

The important commercial question is: To what distance can power be transmitted? The relation between distance and voltage is well known. The same weight of copper can transmit with equal efficiency the same power to any distance, provided the voltage is increased directly as the distance is increased. The limiting commercial ratio between voltage and distance is easily found. If the distance be three miles per 1000 volts and the loss 16%, the cost of copper is about $20.00 per H. P. The interest on the latter investment is about $1.00 per year. A distance in miles equal to three times the number of thousand volts may therefore be covered without an excessive annual charge per H. P. for copper. The limits to the voltage which are practicable depend principally upon the insulator and upon the loss between wires.

The Insulator—The two fundamental requirements are dielectric strength sufficient to prevent puncture, and a size and form which will prevent the passage of the current around the insulator. A given insulator will be adequate for a higher voltage where the atmosphere is comparatively pure and dry, than it will be under other conditions. The rapid progress which has been made in the design and construction of insulators during the last few years, will doubtless provide an insulator which will accom-

modate the highest voltages that can be used due to other limitations. The insulator therefore while remaining the critical point in a transmission system will probably not determine the limit of practicable voltages.

Loss Between Wires—The loss between bare wires at high voltages seems to determine a positive limit, beyond which the voltage cannot be increased. This loss is subject to variation due to diameter of wire, distance between wires, and wave form of the E. M. F., but the variations which may occur under favorable commercial conditions locate the point of increase of loss about 50,000 or 60,000 volts. Under favorable conditions this may be raised somewhat, but it is not probable that any material increase can be made.

Amount of Power—The amount of power to be transmitted involves some interesting commercial limits. There are certain elements in a transmission which do not vary greatly with the amount of power transmitted. Thus, the charging current to the line will be practically the same whether the wire will transmit 1000 H. P. or 100 H. P. If the charging current happens to represent 300 H. P. it would be insignificant in one case, but for the smaller output it would require generating apparatus several times that necessary for the actual power.

It is not mechanically practicable to use wires as small as would be sufficient, in so far as conductivity is concerned, for transmitting a small power. For example, a No. 7 copper wire, which is as small as is ordinarily used, if employed in a 3-phase circuit fifty miles in length, will transmit over 1000 K. W. at 40,000 volts with 10% loss. If only a few hundred kilowatts were to be transmitted, the cost per K W. would be excessively high, and on the other hand a lower voltage could be used without undue loss. In some cases, indeed, where a high voltage is used for small power, as for example on a branch circuit, an iron telegraph wire would have ample conductivity. In other cases an aluminium wire could be used to advantage, as an aluminium wire of the same conductivity as a copper wire has only about half the weight, and possesses greater mechanical strength in comparison to its weight.

It may also be noted that high-voltage transformers cannot be economically built for small output, as the insulation spaces required are so large. The cross-section of the copper is often not more than 10 or 20 per cent. of the area of the opening in the

iron. The cost per K. W. increases very rapidly when the size of transformer falls under a few hundred K. W.

Cables and Conduits.—The overhead transmission line has been considered, and its limitations are the insulating strength of the insulator and the losses through the intervening medium. In a cable or a conduit the insulation must be provided continuously instead of at points a hundred feet apart. Rubber covered cables are made for 10,000 and 20,000 volts but it is quite possible that it will not be commercially practicable to make cables for much higher voltages. The effect of continued electric stresses on the insulation of the cable, which is an unknown factor, may prove to be a very important one. A conduit composed of a pipe containing oil, in which the wires are separated by glass tubes has been proposed. Many mechanical difficulties arise in constructions of this kind; the cost is high and the action of continued high voltages on solids and liquids opens a field which is little known. A suitable insulation on the wires on high-voltage lines may enable higher voltages to be used than can be used with a bare wire.

Liquid air with its high insulating properties and the low temperature and consequent high conductivity which it would give to a conducting wire may enable us to use air insulation in a new way.

Difficulties and Precautions.—High voltages have been referred to in this paper with perhaps undue familiarity. Familiarity with high voltages is not one which breeds contempt. A voltage which can produce sparks several inches in length, which can be felt through several feet of air, which causes hissing sounds, which produces luminosity and which in a confined room generates strong odors of ozone, is one which creates profound respect. Dangers and difficulties accompany it and the highest intelligence, vigilance and excellence must be employed to avoid accident and ensure success. While ordinary types of construction do not seem to reach their limitations until some 50,000 volts is reached and pressures of this order have been and are in regular use, nevertheless they are not to be used indiscriminately or where they can be avoided. There are difficulties enough in handling 15,000 and 20,000 volts. As the pressure is raised the liabilities to trouble increase at an alarming rate. It is, however, a fact that these voltages have been and can be used, and also that no new or modified methods of transmission will be required before 50,000 or 60,000 volts can be employed for distances up to 150 or 200 miles.

APPENDIX A.

Instruments and Methods Used in Telluride Measurements.

[Extract from report of Mr. Mershon.]

"*The Wattmeters*—At first, all the measurements of power were made in the low-tension circuit. The attempts to measure the power delivered to the line by taking the difference in the readings of the wattmeter in the low-tension circuit of the transformers when the lines were on and when they were off, proved worse than useless. This was due to the fact that throwing on the

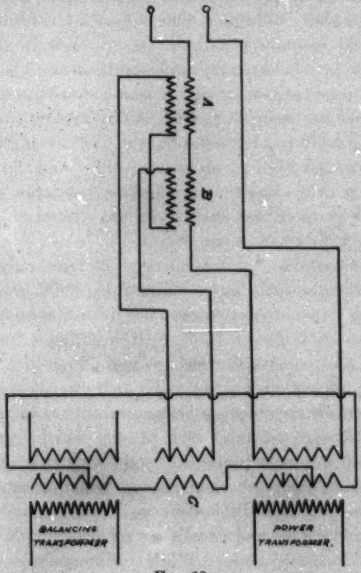


Fig. 18.

lines distorted the E. M. F. wave impressed on the transformer. As a result, at low voltages, readings obtained in this way indicated a negative line loss, and it was only when the voltage was raised to such a point that the line loss was greater than the reduction in iron loss, due to the E. M. F. distortion, that positive results could be obtained; such results were of course incorrect. In order to overcome this, it was determined to balance on the wattmeter the effects of the iron loss in one of the power transformers against that of the other in such a manner that both transformers would be subject to the same E. M. F. distortion, and the iron loss would therefore at no time register anything on the wattmeter. The line loss could then be measured directly. This was accomplished as is shown in Fig. 18.

"Here the transformer which supplies the line is designated as the 'power transformer', while that which is used in balancing the iron loss of the power transformer is called the 'balancing transformer'. As was stated in the description of the transformers, the power transformer has four of its low-tension coils in multiple for receiving power, while the fifth or middle low-tension coil is independently used in connection with the measuring instruments. This middle coil of each transformer is shown in the sketch, and it is through these coils that the balancing transformer receives its voltage. That is, one third of the middle coil of the power transformer feeds one-third of the middle coil of the balancing transformer. With such an arrangement, the balancing transformer receives practically the same wave form as that impressed upon the balancing transformer, no matter what the amount of wave form distortion may be. A is the field coil of the wattmeter. It has two windings. Through one of them, the primary winding, passes the current to the power transformer; through the other, the secondary winding, passes the balancing current—the current to the balancing transformer. As these currents are in opposite directions in their respective windings, when adjusted to the proper values, their effects on the shunt coil of the wattmeter annul each other. It is evident that if A only were used, a balance for iron loss when the lines were off would not necessarily mean a balance when the lines were on, because the change in current due to putting the lines on would cause a change in the reactance E. M. F. of the secondary of the wattmeter field coil, and consequently a change in the balancing current through this secondary. The air transformer B is therefore used: B is preferably, but not necessarily, exactly similar to the field coil A, and supplies an E. M. F. in its secondary exactly equal to and in step with that of the secondary of A. These two secondaries are connected in series, so that their E. M. F.'s oppose, and through them both, is sent the balancing current. The secondaries of A and B are not connected directly in series with the circuit connecting the middle coils of the power transformer and balancing transformer, but are included in this circuit through the medium of a series transformer, C. C makes possible the adjustment of the balancing current to the value necessary for zero wattmeter reading when the lines are off, and it, or some equivalent device, is necessary because of the impossibility of securing two transformers with exactly the same iron loss. Indeed, in this particular case the ratio of the hysteresis to the Foucault current loss differed sufficiently in the two transformers to necessitate adding in shunt to one of them an ohmic resistance which made up for the lack of Foucault current loss in it. This method of reading power is, if properly carried out, a most admirable one, and has the advantage that the instruments to be handled are all in the low-tension circuit. The balance may be obtained without difficulty, and when once properly obtained holds through all ranges of voltages and distortions of wave form. Tests of this balance were made repeatedly with the lines off, by varying the impressed E. M. F. through wide ranges and distorting the E. M. F. wave, the distortion being produced by introducing in series with the power transformer large amounts of both resistance and reactance. In every case the balance was perfectly preserved. There is one drawback, though not a serious one, to the method as here employed. The power transformer, because of the load upon it, heats up faster than the balancing transformer, and the balance is in consequence impaired. The amount of unbalancing is, however, small, even for wide difference of temperature, and it can be easily corrected for by means of zero readings taken before and after a set of observations. This unbalancing,

due to unequal heating, could be rendered negligible by placing the power transformer and the balancing transformer in the same tank of oil.

"Although in this case the balancing transformer was of the same size as the power transformer, it may be much smaller, though both transformers should be worked at the same induction. Of course it is not necessary that the balancing transformer have a full set of windings. It need only have a coil suitable for receiving E. M. F. impressed upon it

"The wattmeter actually used in this work (shown in Figure 19) consists of a field coil so mounted that a Weston wattmeter can be slid in and out of it, and different ranges thus obtained. The scale originally on the wattmeter was replaced by one of equal parts. The wattmeter's own field coil is not used at all, the field being supplied wholly by the large external field bobbin. The voltage impressed upon the wattmeter shunt coil was at first obtained from the auto-transformer above mentioned, but later it was obtained directly from one-third of the middle coil of the power transformer by the use of an additional resistance or multiplier. The winding of the field bobbin consists of 27 turns

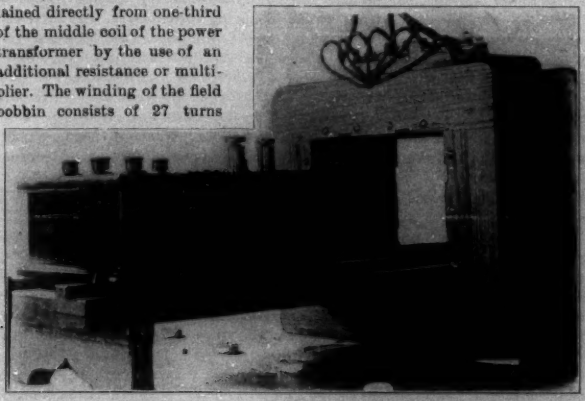


FIG. 19.—Wattmeter with External coil, used in Tests at Telluride.

of a cable composed of seven No. 8 double cotton-covered magnet wires which were twisted together after having been separately treated with 'P & B' insulating compound.

"The wires are brought out separately to terminals on the top of the bobbin, and can be used singly or in any desired series or multiple combination. They were, for this work, connected up into two sets, forming the primary and secondary of the wattmeter coil. The size of this field coil, necessitated by the size of the wattmeter box, gives it a large reactance, and as this has added to it the equal reactance of the air transformer, the reactance of the combination is considerable. This is objectionable because of the consequent distortion of the generator E. M. F. wave, for though the results obtained under these conditions are accurate, they are in some cases the results of conditions differing widely from those which will ordinarily be met with in practice. The combined react-

ance of the field coil and the air transformer at a frequency of 60, when passing a current taken by a power transformer supplying the line, is 2.88. The current used in obtaining this figure probably differed somewhat from a sine wave. If the wattmeter were specially constructed with a view to this work, the movement being surrounded as closely as possible by the protecting case, the external field coil into which the movement projected could be made small enough to reduce the reactance to a negligible quality. In designing a wattmeter for this work, it should be borne in mind that it must measure under the condition of a very small power-factor.

"In these notes the term 'Weston wattmeter' is meant to include the field bobbin of the wattmeter and the air transformer used in connection with it.

"After the above wattmeter had been in use for some time, another was obtained for use in the high-tension circuit. It is a Thomson inclined-coil instrument, whose field coil was rewound for this work. In connection with this wattmeter are two external resistances—the one with a resistance of 1,202,-300 ohms, for use in series with the shunt circuit of the wattmeter; the other with a resistance of 3,495 ohms, being equal to that of the wattmeter shunt circuit and intended for use in shunt to the latter, in which case the wattmeter

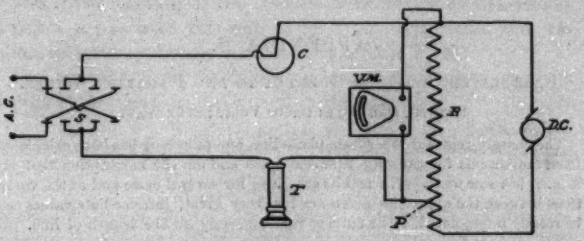


FIG. 20.

shunt coil receives only one-half of the current in the shunt circuit. When in use, the case of the wattmeter was connected to one of the wattmeter shunt terminals, so that the inside and case of the wattmeter were always at the same potential and the case formed a screen against any external electro-static effects. This wattmeter was of considerable value as furnishing a means of studying the effect of the distortions due to the Weston wattmeter, and also to the readings at low frequency, since in the latter case, it was necessary to use both transformers as power transformers, which left nothing for use as a balancing transformer. In the notes this wattmeter is designated as Thomson wattmeter.

"*The Ammeters*—The ammeters used were two Thomson inclined-coil instruments. They had a capacity of one-half and two and one-half amperes respectively. They were put directly into the high-tension circuit, the cases being connected to one terminal of the instrument.

"*The Wave Form Apparatus*—The method of taking wave forms was that devised and published by the writer, [Mr. Mershon], in 1891. It is an instantaneous potentiometer method, employing a telephone receiver to indicate a balance. The connections are those shown in Fig. 20.

"A C is the source of the alternating E. M. F., whose wave form is to be plotted, S is a double-pole switch for reversing the alternating current terminals, C is the usual instantaneous contact device, T is a telephone receiver. V M is a D. C. voltmeter—in this case the Weston laboratory standard, R is a resistance along which the contact P can be moved. D C is a source of direct current—in this case a direct current dynamo feeding the resistance R. The contact C being set at any desired point, the value of the E. M. F. at the instant of contact is determined by moving P backward or forward until there is no sound in the telephone T. The reading of the direct-current voltmeter V M gives the desired value. The E. M. F. A. C was obtained from the same source as the E. M. F. for the A. C. voltmeter, *i.e.*, from an auto-converter connected across one-third of the middle coil of the power transformer.

"*The Speed Indication*—The indication of proper speed, or rather frequency, was obtained from the vibration of a weighted steel wire hung in front of the poles of an alternating electro-magnet energized by the machine supplying power. The wire always vibrated at the frequency for which the suspended weight was adjusted, and ceased to vibrate when there was any appreciable deviation from this frequency."

APPENDIX B.

Calculated Charging Current to two Parallel Wires.

Length, One Mile; 10,000 Volts; Sine Wave.

The charging current to a single-phase line one mile long has been calculated from the formula for capacity between wires and on the assumption that the E. M. F. is a sine wave. The results are given for several cases and as the variations between the quantities given are not very great, intermediate values can be readily interpolated. The current varies directly as the length of line, the voltage and the frequency.

Size of Wire—B & S.	No. 8	No. 4	No. 1	No. 0000	1" diam.
Distance between centers of Wires.	Amperes at 60 cycles.				
12 inches.	.032	.035	.038	.0414	.053
24 "	.0284	.0309	.0328	.0362	.043
48 "	.0252	.0274	.029	.0313	.0369
	Amperes at 25 cycles.				
12 inches.	.0133	.0146	.0158	.0172	.0221
24 "	.0118	.0130	.0137	.0151	.0179
48 "	.0105	.0118	.0121	.0130	.0154

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, September 28th 1898.

The 127th meeting of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS was held this date at 12 West 31st Street, and was called to order by President Kennelly at 8:20 P. M.

The Secretary read the following names of associate members elected at the meeting of Council in the afternoon.

Name.	Address.	Endorsed by
CARTER, FREDERICK WILLIAM	Lecturer in Electrical Technology, City and Guilds of London Institute, Exhibition Road, London, S. W.	Edwin J. Houston. A. E. Kennelly. A. J. Rowland.
COLEMAN, WALTER H.	Supt. and Treasurer, Andover Electric Co., Andover, Mass.	Chas. B. Burleigh. Sidney B Paine. C. D. Haskins.
DOHERTY, HENRY L.	General Manager and Engineer, Madison Gas and Electric Co., Madison, Wis.	M. C. Beebe. D. C. Jackson. C. F. Burgess.
FRANK, GEO. W., JR.	Secretary, Treasurer and General Manager, The Kearney Electric Co., Kearney, Neb.	J. G. White. W. F. White. D. C. Jackson.
MANSFIELD, R. H., Jr.	Electrical Engineer and General Manager, Ward Leonard Electric Co., Bronxville, N. Y.	H. Ward Leonard. F. S. Holmes. F. A. Pickernell.
MILLER, KEMPSTER B.	Chief Electrician, Western Telephone Construction Co., 33 Elaine Place, Chicago, Ill.	S. G. McMeen. Fred'k Bedell. Harris J. Ryan.
ROSENBUSCH, GILBERT	Engineer, Sprague Electric Co., South Orange, N. J.	Frank J. Sprague. Philip Torchio. R. W. Pope.
THOMPSON, JOHN WEST	Supt. Cia. de Luz'y Fuerza Motriz Electrica, Guadalajara, Mexico.	F. A. C. Perrine. F. V. T. Lee. F. E. Theberath.
TRIPIER, HENRI	Counsel and Technical Engineer, of the Campagnie des Transports Electriques del Exposition, Paris, France; residence, 16 rue Ganneron, Paris, France.	Chas LeBlanc. Ralph W. Pope. W. J. Hammer.

WAGNER, HERBERT A	Gen. Supt., Missouri, Edison Electric Co., and also with Wagner Electric Mfg. Co., 415 Locust St., St. Louis, Mo.	T. C. Martin. Joseph Wetzler. Wm. E. Geyer.
WILLIAMS, WILLIAM HENRY	Professor of Mechanical and Electrical Engineering, Montana State College, Bozeman, Mont.	D. C. Jackson. S. B. Fortenbaugh F. R. Jones.

Total 11.

THE PRESIDENT:—The paper for the evening is on the "Photometry of the Enclosed Alternating Arc," and copies of the paper are already in your hands. We are not fortunate enough to have Prof. Matthews with us, but the Secretary will kindly read the paper on his behalf.

(The Secretary read the paper.—See p. 599, Aug.–Sept. issue.)

Discussion.

Mr. Louis B. Marks :—It is very seldom that one is treated to so concise and lucid a description of the limitations of arc-light photometry as is contained in this able paper by Messrs. Matthews, Thompson and Hilbish. For my part, I think that the first part of the paper, which goes into detail regarding photometry, is perhaps more important than the latter portion, which gives some measurements of the candle-power of the alternating current arc. So that I trust you will bear with me for a few moments while I consider what is said in the paper with relation to the photometry of the arc.

Prof. Matthews says that the first reason for the difficulty in determining the luminous yield of an arc, is the marked difference in quality between the light of the arc and that of the standard. This is perhaps one of the most important difficulties in arc-light photometry. We are apt to be confronted, as Prof. Matthews points out, with a difference of color between the arc-light and the standard. This makes it very difficult to set a photometer carriage properly so as to obtain the true relative candle-power of two sources of illumination which differ in color. You will notice that in this paper the Hefner amyl-acetate lamp is taken as the standard. The tinge of the flame of this lamp is quite reddish, whereas the tinge of the alternating current arc, as you all know, is decidedly violet; so that, strictly speaking, we are comparing a violet light with a light that is red in color. Comparative candle-power measurements of this kind are limited in value and are often misleading.

I find on page 600 the statement that "the inner, opalescent globe absorbs the rays of short wave-length in greatest proportion, a fact which brings the color of the arc nearer that of the standard."

Now, the question occurs to me, if we use such an opalescent globe, thereby altering the quality of the issuing light, are we obtaining a fair comparison between the candle-powers of the two lamps? The nature of the light is undoubtedly changed in passing through this tinted glass, so that the results will depend upon the composition of the glass of the enclosing bulb. There is also another question, namely, the amount of light cut off by this opalescent globe. I am not alluding to this now, but simply to the effect of the difference in quality of the light caused by the interposition of a glass globe absorbing a large percentage of the violet or shorter wave-lengths of light. Unless a clear glass globe be used, this modification in the character of the rays may considerably impair the value of the comparative measurements.

It is well known that light of one color impresses the eye with quite a different force than light of another color, and the intensity of the sensation—the physiological sensation—determines to

a considerable extent the power of the light. I think that Helmholtz stated that the sensation was a function of the luminous intensity and varied with different kinds of light. Of two lights, one of which is rich in blue and the other rich in red, the sensation increases more rapidly for the red and decreases more rapidly for the blue for the same range of luminous intensity. In order to make this a little clearer, suppose we have two lights, one of which is rich in the shorter wave-lengths of the spectrum, and the other of which is rich in the longer wave lengths. Now, suppose these lights have the same candle-power exactly. If we then simultaneously double the quantity of light thrown by each on the photometer screen, we will find that the yellow light or the red light, as the case may be—the light of longer wave-length—will appear brighter than the light of the shorter wave-length. Whereas, if you then suddenly decrease the quantity of light in each case, you will find that the light of the shorter wave-length, that is the blue light, will appear brighter than the yellow light. Now, here is a condition of affairs that depends, it appears, on physiological causes, and is not taken into consideration by the photometer in the measurement of the power of a source of illumination. I lay stress on these points because in interpreting the figures given by the authors of this paper, we must bear in mind that, although the readings have been undoubtedly most carefully taken, the candle.power measurements, which at best can have but a relative value, are subject to numerous limitations.

On page 600, near the bottom, the authors refer to the second obstacle to careful measurement, namely, the variability of the quantity to be measured. "These variations," they say, "are largely due to the wandering condition of the arc—a peculiarity that is especially noticeable in the open alternating arc, and in both types of the enclosed arc." And then they add, "Indeed, it is to this feature of the enclosed arc that the flat-ended carbons are due." Now, is it not just the other way? Is not this feature of the enclosed arc due, if anything, to the flat-ended carbons? The flattening of the carbon ends is due, not to the wandering of the arc, but to the absence or partial absence of oxygen in the enclosing bulb. When the carbons are enclosed, the oxygen is excluded, or has very limited access, and the tips of the carbons are no longer subject to the same conditions of oxidation as exist in the ordinary arc which burns in free air. Hence, the carbon ends become blunt or flattened. The arc being quite small in cross-section and tending to lengthen as the carbons burn away, seeks the path of least resistance, and so gradually travels over the surface of the carbon ends. This wandering, or "hunting" as it is sometimes termed, continues as long as the lamp is in action, and appears to be primarily brought about by the flattening of the carbon ends.

On page 601 is mentioned a new instrument which I think

will be a boon to all those who have use for a photometer. The mechanical device designed by Prof. Matthews for recording a setting as soon as it is made, will enable us to take quick and accurate readings. Many of us who have experienced the visual fatigue incident to the use of a light in the photometer room, will give a hearty welcome to this new device. Prof. Matthews is to be congratulated on the invention of this simple and ingenious arrangement, which I trust will quickly find its way into photometer rooms throughout the country.

The third point mentioned is the question of the validity of the term "candle-power." Although I do not intend to take up your time now with a discussion on this particular point, I trust that others who have gone into it more fully than myself will expand on what is said here especially in relation to the term *luminosity* as compared with candle-power. This question is of great importance. It is safe to say that no measurement of candle-power *per se* can give us a complete expression of the true illuminating power. One light may have as much candle-power so-called as as another, and have a much smaller illuminating power. I think the question referred to here, on page 602, is one which should command our serious attention.

In making their measurements the authors used a Kruss-Bunsen photometer and a swinging crane in connection with a 45 degree mirror. I have made use of this particular arrangement quite often, and it has occurred to me that possibly there is such a thing as selective absorption in the mirror. The authors employ glow lamps in determining the reflecting power of the mirror. In order to get a correct value of the coefficient of reflection they operate the incandescent lamps at 95 volts, at 105 volts, and so on up to 137 volts. They state that "although the change in the quality of the light was very marked in this experiment, the results do not indicate any regular change in the coefficient of reflection." Their maximum value for this coefficient is .836; their minimum, .782, making a difference of about 5% in the reflecting power of the mirror. Although they do not find the value of the coefficient to follow any regular law with the increase in temperature in the filaments, the authors may not be justified in taking the mean of these various determinations as a fair value of the coefficient of reflection for the arc. Have you ever noticed an enclosed arc lamp, especially an enclosed alternating arc with clear outer globe, on the street in front of a show-window? At night when the current is on, if you look at the lamp the small opalescent globe appears to be filled with a soft white light; but if you observe the reflection in the window-glass, the small globe seems to emit a strong violet light. Now the authors noted the same phenomenon when they lit their arc and looked into the mirror mounted on their photometer. But they probably erred in assuming that measurements of selective absorption based on the reflection of an incandescent filament at high temperature, will hold for the arc.

As to the candle-power measurements given for the alternating current arc I shall have very little to say just now. I note that the curves of distribution are carefully worked out; that they have all the kinks with which we are more or less familiar, due to reflection of the light, to the shape of bulbs, to the inequalities in the glass, to the distortion of the plane of the carbon ends, etc., etc.

I also note, and I call your attention to this point, that the authors have, I believe, taken all their candle-power measurements for small opalescent globes. They have not given us any measurements with small clear globes in their lamps. So in comparing the results of the authors and those of other experimenters, it is well to bear in mind that there may be a difference of perhaps 30 per cent or even more between these candle-power values and those given in tests of lamps in which the small globes are clear.

I notice that the authors refer to some tests of Dr. Nichols'. As far as I can remember, Dr. Nichols used clear globes in all of the tests that he has published on standard lamps,—at least all that I have seen. The difference in density in the case of opal or opalescent glass globes is very marked, and those who have used enclosed alternating arc lamps much will know that some of the small globes are very dense indeed and cut off as much as 50 per cent of the light. I do not know just what percentage of light is cut off by the globes that the authors used. They do not mention this in their paper, and consequently we are left in the dark as to quite a vital point.

As far as the ultimate results are concerned, that is, the actual efficiency of an enclosed alternating arc as compared with a direct, I find that they give for lamp A, alternating current type, the curve of which is on page 604, and the data on page 605, 2.96 watts at the arc per mean spherical Hefner unit; and for lamp D, which is the direct current lamp, supposed to be a typical lamp, data on page 615 and curve on page 616, 1.98 watts at the arc per mean spherical Hefner unit. Thus there appears to be a difference in candle-power output of over 50 per cent. in favor of the direct current lamp. But unfortunately the authors took two lamps whose power at the arc was different. The alternating lamp consumed less power at the arc than the direct. If both lamps consumed the same power at the arc, it is probable that the difference in favor of the direct current lamp would fall to 35 per cent. or less.

I intended to make a few remarks regarding some other parts of the paper. But I am aware that there are others who have something to say and shall therefore close my discussion at least for the present. I thank you very much for your kind attention.

MR. W. H. FREEDMAN:—Mr. Marks, in his very able discussion of this paper, has left very little to be said. I will, however, add a few remarks, and try not to repeat anything that he has

alluded to, except the one point in regard to the hunting of the arc. Now, it seems to me that if the oxygen were excluded from an arc so that the carbon could not go off in carbon mon-oxide and di-oxide vapors, the ends would be flat, and in the open arc they assume that more conical shape on account of this oxidation of the carbon. Accordingly, it seems to me that on account of their being flat, as the carbon is vaporized, a little pocket tends to form, and so increases the distance; therefore, it will require more energy to keep up the arc between those two points, and consequently, due to the resulting stresses, the arc wanders to a place where less energy will maintain it. Nature is rather lazy, and all operations go on with the least expenditure of energy. Therefore, this arc wanders so as to always keep up its luminosity and burning, if I may use the word, with the least expenditure of energy. So, in my opinion, that criticism is rather correct, and instead of the flat carbons being due to the wandering, it is exactly the opposite—that on account of the carbons being flat the arc wanders around and so adds to the troubles of the photometrist who is trying to determine its candle-power.

On page 606 the authors make the statement that "the power factor is due to the inductance of the mechanism, as it has been clearly established by Blondel that in the arc itself the electromotive force and current are strictly in phase." Without laying any stress on the use of the word electromotive force, it is perfectly true that the difference of potential between the carbons of the arc is zero when the current through the arc is zero in the case of an alternating arc which is used for illumination, or I should more properly say a self-regulating arc. But I think that statement ought to be somewhat qualified, because if you take an alternating current arc and clamp it rigidly and work it by a hand-feed, if there is no self-induction in the current, then that statement is not true, and the current has rather gaps of zero value. It does not pass through zero at a point; it has a zero value for quite an appreciable period of time, so that there is a zero line in the current. That being the case, there is a power factor in the arc which is slightly different from the power factor in a simple alternating power circuit, in that we cannot strictly say there is a phase between the electromotive force and the current, but on account of the current not following the sine law, we will find that taking voltmeter and ammeter readings and multiplying the two together, the apparent watts are a great deal larger than the readings of the wattmeter, and we have a power factor in this kind of an arc. So unless that statement is qualified it seems to me it is erroneous to state that the power factor is entirely due to the mechanism of the lamp. There is no doubt that the self-induction in the lamp causes the phase of the current, but unless that happens to be exactly balanced with respect to the distance, etc., the arc might not go through the zero values at a point, and if that is the case, then the total power factor is

due partly to the mechanism and partly to the shape of the current wave in the arc.

Now, coming to the measurements of the candle-power, personally, not being an enthusiast on photometry, I think that it adds slightly to the complication of photometric measurements for everybody to use their own units, and it seems to me, as far as engineers are concerned, it is usual to speak of candle-power. I am willing to confess that I had to look up what the value of the Hefner unit was before I could compare this paper with any other published results which heretofore have always appeared in candle-power. If I remember correctly, Dr. Nichols, of Cornell University, said that the best way to measure candle-power, the most certain way, is to use the Hefner unit, which is 88 per cent. of the British candle. If we forget that number, however, we are somewhat at sea in comparing different papers.

Then when it comes to the measurement itself, Mr. Marks has already pointed out that although carefully made, the results are not absolute, as one curve presented by the authors themselves shows—the curve on page 611. They present a lamp, C, with and without a milky globe. When they put the milky globe on, they of course get the smaller distribution of luminous intensity, but, strange to say, the upper portion seems to be of the greater candle-power or Hefner unit, and they advance the explanation, which is undoubtedly correct, that the lower half is of less intensity on account of the absorption of the globe. That in itself must bring to mind the fact that if we change the globe we are going to get an entirely different distribution. The distribution which they present on page 616 for a normal direct current lamp is one which is entirely different from any that were obtained at Columbia University—that being another argument or another evidence to show that the globes which were used in each case were different, and the difference in the form of the curve being, no doubt, largely due to that fact. I also think that the curve on page 606, perhaps by some inadvertence of the printer, has become reversed. The curve given by Uppenborn shows the greater area on the top. I think that the greater luminous intensity must be at the bottom and not at the top. So those butterfly wings ought to be inverted.

I will close by merely stating that, so far as I know, these are the first results and figures that have been published on the alternating current arc with respect to its distribution of luminous intensity, and from that standpoint, bearing in mind the photometric limitations, I consider the paper rather valuable as being an addition to the data available to an engineer.

THE PRESIDENT:—I understand that we have Captain John Millis, of the Lighthouse Board, with us this evening. If so, I should be pleased to hear from him upon his aspect of this subject.

CAPTAIN MILLIS:—Mr. President, I am somewhat disappointed

at being discovered, since I would have preferred to be only an interested listener in an obscure corner. There is very little that I can add to what has already been said on this subject, but possibly I may submit one or two remarks presently. I should like very much to ask the gentleman who first addressed us to give us a somewhat more explicit idea as to what he means when he says that one light may have a greater candle-power than another, but a less luminous intensity. I do not understand exactly what he means, and I should be very glad if he could make this a little clearer.

MR. MARKS:—I think that possibly in a few words I may be able to give my view of the matter. The candle-power of an arc, as I understand it, simply represents its power as compared with a standard source of light known as the candle. For instance, we have an ordinary standard candle. It burns 120 grains in an hour, or given standard time. We compare an incandescent lamp with that candle, and by the aid of the photometer obtain a ratio representing the illuminating power of the incandescent lamp in terms of the candle. From that we get the power of the arc lamp. Supposing the power of the arc lamp thus photometrically measured is 400, this would indicate that it has 400 times the illuminating power of the candle which was used as the source of the comparison. Now let us take the arc light and put it in a reading-room, and read by it. Then let us take it and put it in the fields and distinguish the color of the trees and natural objects by it. I ask you, will the true illuminating power of that arc lamp be 400 in both cases? I also ask you, will the illuminating power of an arc lamp not depend upon the use to which the light is put? Will it not depend upon its power of bringing out the true colors of objects, as well as of aiding the eye in seeing and distinguishing objects? I say that the illuminating power of a lamp depends largely upon the quality of the light. And the quality will depend upon the proportion of rays of short wave-length and of long-wave length in the light. In some cases, as in bringing out the colors of natural objects, and so on, the proportion of shorter wave-lengths in the light is all-important; while as far as the power of illumination as applied simply to black and white is concerned, the importance of the longer wave-lengths is paramount.

Now in the production of *candle-power* the various rays of the spectrum do not count in proportion to their energy; the influence of the shorter or more refrangible rays is much less than that of the longer wave-lengths. Indeed some of the rays of short wave-length, at the extreme violet end of the spectrum, do not enter to any appreciable extent into the production of candle-power; yet these very rays often constitute a most important factor in the illuminating power of an arc light. This is what I mean when I say that the candle-power of an arc is not a measure of its illuminating power and that one lamp may have as

much candle power as another and yet have a much smaller illuminating power. As Dr. Nichols pointed out in a paper before this INSTITUTE in 1889, candle-power is a well-nigh meaningless term and may give us a very misleading value of the power of illumination of a light. He records a number of tests which prove quite conclusively that even though two lights have the same candle power, the illuminating power of one may be widely different from that of the other. The reasons for this difference have already been given. I do not know whether I have gone into the matter too much at length or not, or whether I have made myself clear; but I shall ask the President, Dr. Kennelly, whether I have explained to his satisfaction why it is that one lamp may have more illuminating power than another without having more candle-power.

THE PRESIDENT:—I think we all understand Mr. Marks as to his meaning of the terms. These terms are unfortunately given so many different meanings by different men that it is quite easy to misinterpret them until they are explained.

CAPTAIN MILLIS:—The gentleman has referred to exactly the point that I was going to speak about. I think, however, that he gives us a somewhat incorrect impression in passing from something which we regard as the measurement of the power or intensity of a light, in a physical sense, to something which is rather a question of judgment, of individual preference, or of adaptability to the conditions, and I must still differ with him in his view that we can properly say that a light which has a greater candle-power than another may have a less luminous power. Both terms imply a measurement which requires a unit in determining the candle-power, but for luminous power, as the gentleman has just explained the term, I do not understand that any fixed unit or standard is possible. These considerations suggest the fundamental question of the real basis of all so-called photometry. Is it strictly correct to say that photometry as generally practiced is a physical measurement at all, or does it consist merely in approximate comparisons and attempts to express in figures something which cannot be properly so expressed in a mathematical sense? I think we all remember having learned, in the days of our elementary education, that the measurement or the expression of the value of any quantity was the numerical equivalent of that quantity as compared to a fixed quantity of the same kind which was taken as the unit. That may not be exactly the correct wording, but you get the idea. Now, when we attempt to express the intensity of a light and say that it is so much candle-power, it is not a physical expression of its value in all cases, because the standard is not a quantity of the same kind or quality. Anybody who has had experience in a photometer room knows that it is possible to arrive at an approximate idea of the relative luminous intensities of two lights, whether these lights are of the same color or not. In fact, many of you, perhaps, have attempted,

as I have, to compare a white light with a red one. It is entirely possible to put the movable box containing the translucent screen near enough to the red light so that you can say that the side of the screen illuminated by that light is brighter than the other side illuminated by the white light. Similarly, the box could be placed so that the side of the screen towards the white light is unmistakably the brighter, but when an attempt is made to place the box at a point where the two sides of the screen are equally illuminated, difficulties arise, and only an approximate result can be expected at best. It is very largely so in all photometric comparisons that I have had experience with, except, of course, in comparing two lights that were absolutely of the same quality.

The method of measurement to be used, and the conclusions reached, may be materially affected by the particular use that the light is to be applied to. To illustrate by an extreme case, in the Lighthouse Service the vital question is: How far can a light be seen if you are looking at it directly? While in ordinary cases of artificial illumination the question almost invariably is: To what extent will the light enable you to see other objects? If we wish to determine the power or intensity of a light in the sense of how far it can be seen, a practical way to make a comparison with a standard is to put the standard and the light to be measured where they can both be seen from a distance, and go off until first one and then the other have disappeared. It is perfectly easy to understand that the distance at which the lights disappear respectively enable us to determine their relative intensities. Now, if we have two sources of light, for instance, two candles placed a few feet apart so they will not blend, you cannot see the two candles any farther than you can see one; but if you are near the candles and hold a sheet of paper so that both will illuminate the paper, you have got twice the illumination with the two candles that you would have with one candle. For one purpose two candles are twice as good as one, and for the other purpose one is just as good as two.

I wish to endorse what the gentleman said with reference to the recording apparatus. I think that is something we all wish we had thought of ourselves. I know I have felt the need of it a great many times, and I should think it would be very useful, and would expedite photometric work to a notable degree. I notice the author does not say what sort of scale he uses in deducing the results from the recorded observations. Ordinarily, if used with a photometric bar of a fixed length I should think it would be of great convenience to use a scale graduated as photometric bars frequently are, for a fixed distance between two sources, so that the record would give directly the relative intensity of the two lights. I have found, however, in experimenting with lights of a variety of intensities, that bars of various lengths are required, and that it is more generally convenient to use an ordinary scale of equal parts, as inches and tenths, and

make calculations from the readings, although it is somewhat more tedious.

With reference to photometer rooms in general, there is a suggestion which I desire to make as the result of my experience. I think it is a mistake to paint the inside of the photometer room entirely black. It is a very great convenience, in the handling and adjustment of apparatus, etc., to have as much of the interior of the room white, or at least light in color, as you possibly can. If the end walls and the ceiling and floor are black, and adjustable screens are used to cut off the light from sources which are liable to cause interference with your measurements, it will be possible to have the side walls, or a considerable portion of them, light in color.

With the alternating enclosed lamp described in the paper I have had no experience, but I have had considerable experience with the alternating lamp which is not enclosed. With cored carbons, using proper material for the core, I have failed to find the wandering of the arc that the author refers to. I have found the lamp to burn very steadily and very satisfactorily if the proper quality of carbon, of uniform density, and having a core of proper material, is used.

There was one more point that occurred to me. It seems that the lamp described, giving such extremely variable results with a wandering arc, is a very unsatisfactory light machine, and before I should go into very great refinements of measurement to determine what the candle power of the lamp is, I think I should try to devise something to make it give some approach to a fixed candle power, even if the average were somewhat less than the results it gives now. This lamp certainly appears to be open to considerable improvement.

THE PRESIDENT (Dr. Kennelly):—I think we are indebted to the authors for giving us some measurements upon the alternating current arc lamp which have been badly needed, since the only measurements which have been available hitherto have been for the direct-current arc lamp. I think we are also indebted to them for giving us their measurements in units that we can understand. When we speak about British candles we are often in doubt as to how the candles were obtained, how the measurement was made, and whether the British candles were evaluated from Hefner units by process of calculation. Whereas, by giving the results in Hefner units directly, we know that a definite instrument was employed, which is the most satisfactory that has been obtained up to this time. The results show, as pointed out by preceding speakers, how very indefinite and unreliable the photometry of an enclosed arc is from the engineering point of view. You have a source of light varying with the distance between the carbons and with the current strength supplied to them, with the nature and quality of the carbons, and their distance apart, with the angle of depression or elevation, and also with the par-

ticular quality, shape and dimensions of the enclosing globe. So that you have at least two more variables in this kind of lamp than you have in the ordinary alternating arc lamp, non-enclosed. We know how difficult it is with the ordinary alternating arc or continuous arc, to get steady readings or reliable measurements, and the difficulties are therefore augmented in this case. The fact is that until the absorption of the interior globe is taken into account, it is almost impossible to get a fair criterion of the luminous power of the arc within, so much is apt to be absorbed by the opalescent or semi-transparent globe.

I think that we are apt, as engineers, to forget that arc lamps are not employed, as a rule, by engineers, and that their quality and capability are not always to be determined by the methods which we are wont to employ. We set up an arc lamp in a photometer, measure its candle-power in various directions, compute, it may be, its spherical candle-power, compute its economy or efficiency, or inefficiency, as shown in these tables, and then we decide that one lamp is better than another because it is more efficient, or because it gives more candle-power than another; whereas the ordinary individual who uses an arc lamp and who purchases it is not guided very much by such measurements. At a given cost price he is guided by the appearance of the lamp and by its steadiness, by its freedom from noise, and the length of time it will go without re-carboning. His eye gives him very little intimation as to the real candle-power. If he sees a nice opalescent globe around it and it gives a nice, diffused light, he is very apt to consider that that lamp is much superior to one which an engineer may tell him is much more economical as a luminous source.

As regards measurement of candle-power of arc lamps, I think that, from the engineering point of view, the only fair criterion is the mean spherical candle-power, if only for the reason that the individual candle-power in any particular direction of luminous intensity, at any particular angle or azimuth, is so variable with time; and these wide variations which are shown in Figures 10 and 12, as are pointed out in the paper, are not so much variation of the lamp as a whole, as merely variations in one particular direction, namely that, of the photometer screen.

We have been able to measure the spherical candle-power of an arc lamp by placing a mirror outside the arc and nearly over it, and spinning that mirror at about 400 revolutions a minute in a circle about four feet in diameter around the arc, throwing the light into a second mirror at the axis, and through a tube to the photometer screen. It is not sufficient to merely employ a revolving mirror, because you must cut off the light at different azimuths according to a sine law, and you must have, therefore, a sinusoidal shutter to open the light to full candle-power at horizontal and gradually cut off the light as you bring the mirror either below or above. By that means you can get a closely re-

liable reading of the spherical candle-power in any particular vertical plane, and by slowly spinning the arc lamp upon its own centre, so as to turn successively in all directions, the effect of the combination of revolving the mirror in the vertical plane and revolving the lamp in the horizontal plane, gives you a very close approximation, indeed, at any particular moment to the spherical candle-power in all directions.

[Adjourned.]

DIED.

DAVENPORT:—At Ponce, Puerto Rico, October 26th, 1898, Clarence G. Davenport, formerly Expert and Agent, for the General Electric Co., at the New York offices of the company, No. 44 Broad Street. He was a son of Rev. John G. Davenport, of Waterbury, Conn., and had been in the employ of the General Electric Company for eight years. He enlisted in the 1st Regiment U. S. V. Engineers, and accompanied that regiment to Puerto Rico where he contracted typhoid fever which was the cause of his death. He was elected an Associate Member of the INSTITUTE Nov. 21, 1894.

GALILEO FERRARIS.

A Memorial.

The *Associazione Elettrotecnica Italiana* of Milan, Italy, has undertaken the accumulation of a fund for the purpose of erecting a suitable monument in memory of the late Professor Galileo Ferraris. In order to enable his many American friends to participate in this worthy object, which will assume the form of an international tribute, the Executive Committee has authorized the Secretary to receive any contributions that may be made, and which will be forwarded to the Italian Society, through the agency of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS. Remittances by check or money order will be duly acknowledged, and should be made payable to the undersigned.

RALPH W. POPE,
Secretary.

NEW YORK, June 24th, 1898.

The Institute Badge.

The Council has authorized the sale of Badges of the new design at the following prices, for the different styles.

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The monthly parts distributed to members and subscribers during the year, are not intended for binding, but simply for the use of readers, as the work of the Institute progresses.

After printing the monthly, the papers and discussions are revised, repaged, and the sheets for the annual volume printed from the corrected type, and laid aside till the close of the year. As the index is made for the volume and **not** for the monthly parts, the complete volume sent at the end of the year becomes the permanent record. Upon its receipt the monthly parts are superfluous. They may be returned to this office at our expense, as there is a continual demand for separate copies of papers.

RALPH W. POPE, Secretary.

COPPER WIRE TABLE.

This table gives the WEIGHTS, LENGTHS and RESISTANCES of cool, warm, and hot wires of

MATTHIESSEN'S STANDARD CONDUCTIVITY,

for both Brown and Sharpe (A. W. G.) and Birmingham Wire Gauges (B. W. G.)

It was prepared by the Institute Committee on Units and Standards, personally revised by the individual members of the Committee, and issued with the October, 1893, number of the TRANSACTIONS, forming a part of Volume X.

Mailed separately, price 10 cents. RALPH W. POPE, Secretary,
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